



ELECTRON-ION COLLIDER USER GROUP MEETING 2016

UC BERKELEY, CA, JANUARY 6-9, 2016

1 Le Conte Hall

QCD in 2025 (in both ep and eA)

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Acknowledgement: Some of the physics presented here are based on Summaries of the “QCD and Hadron Physics” and “Phases of QCD Matter” - the DNP Town Meetings

Quantum Chromodynamics (QCD)

A beautiful and self-consistent QFT of quarks and gluons

| | | |
|----------------|----------------|--|
| Fields: | $\psi_i^f(x)$ | Quark fields: spin- $\frac{1}{2}$ Dirac fermion (like electron) |
| | | Color triplet: $i = 1, 2, 3 = N_c$ |
| | | Flavor: $f = u, d, s, c, b, t$ |
| | $A_{\mu,a}(x)$ | Gluon fields: spin-1 vector field (like photon) |
| | | Color octet: $a = 1, 2, \dots, 8 = N_c^2 - 1$ |

QCD Lagrangian density: ... Bardeen, Fritzsche, Gell-Mann, Leutwyler, 1972,3

$$\begin{aligned}\mathcal{L}_{QCD}(\psi, A) = & \sum_f \bar{\psi}_i^f [(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij}] \psi_j^f \\ & - \frac{1}{4} [\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc}A_{\mu,b}A_{\nu,c}]^2 \\ & + \text{gauge fixing} + \text{ghost terms}\end{aligned}$$

QED Lagrangian density – force to hold atoms together:

$$\mathcal{L}_{QED}(\phi, A) = \sum_f \bar{\psi}^f [(i\partial_\mu - eA_\mu)\gamma^\mu - m_f] \psi^f - \frac{1}{4} [\partial_\mu A_\nu - \partial_\nu A_\mu]^2$$

- ✧ **QCD is much richer in dynamics than QED**
- ✧ **QCD is universally recognized as the correct theory of strong interactions**
- ✧ **But, No nucleons, No mesons, No nuclei, No XYZ, ...**

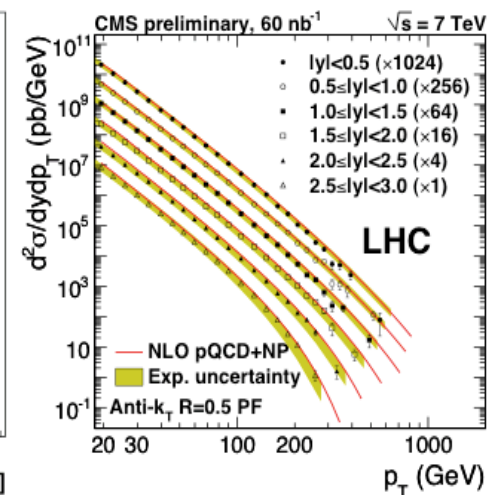
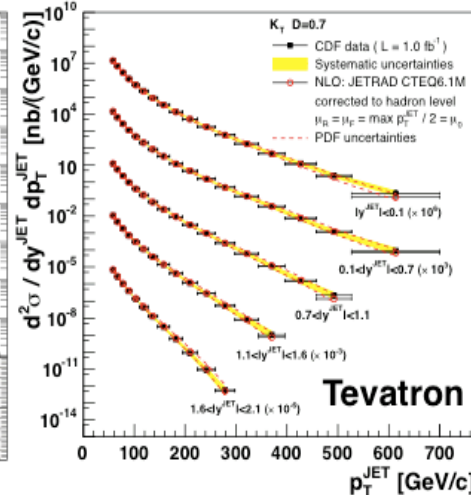
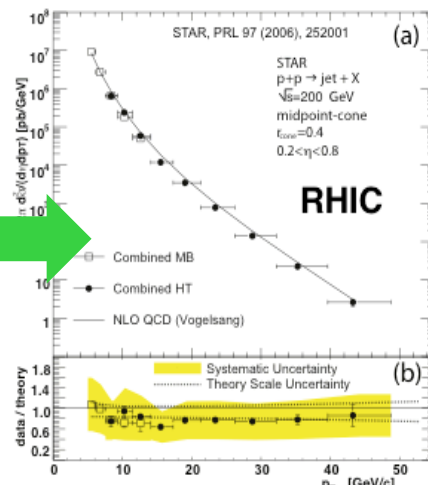
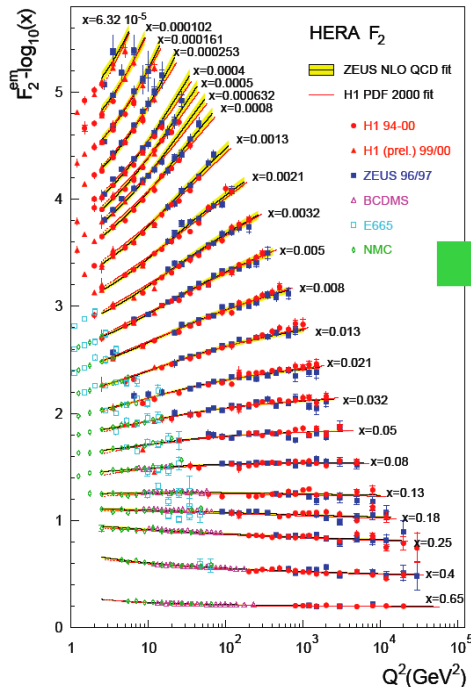
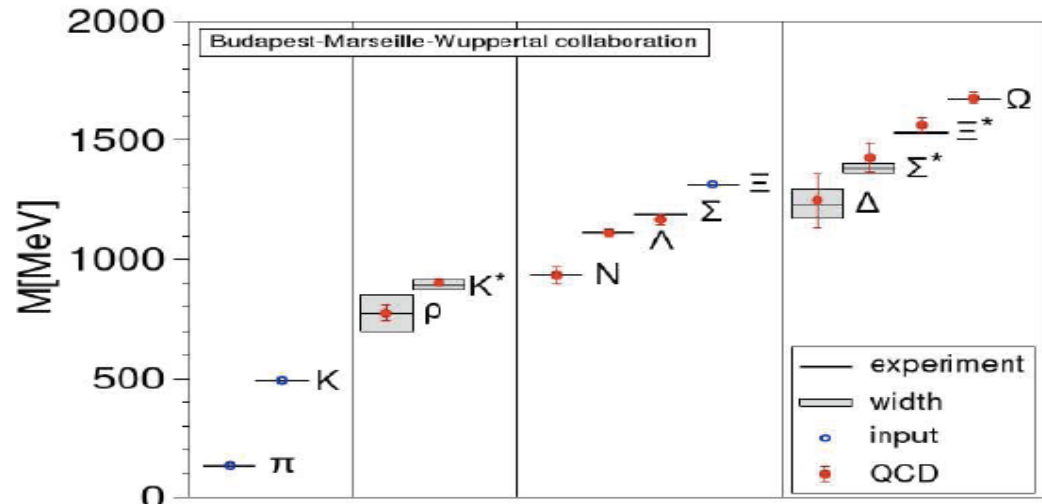
QCD has been successful

□ @low energy:

Hadron mass spectrum
from lattice QCD

□ @high energy:

Asymptotic freedom
+ perturbative QCD



Measure e-p at 0.3 TeV (HERA)

Predict p-p and p-p at 0.2, 1.96, and 7 TeV

Outline for the rest of my talk

□ “Big” questions/puzzles about QCD (ep + eA)

Almost all are connected to the role of the glue, which is “dark”, not “free” in isolation, but, interact with itself, ...

□ What we could learn in next 10 years or so (ep + eA)

JLab12, COMPASS + RHIC, FNAL, LHC, ...

Improved theory calculations, Lattice QCD, ...

□ QCD in 2025

Theory (Confinement – hope?)

Improved and better controlled probes for
hadron structure, emergency of hadrons, ...

Ready for EIC, ...

Lattice QCD

hadron structure, nuclear force, ...

□ Summary

See also Kovchegov’s talk

“Big” questions/puzzles about QCD (ep + eA)

❑ How quarks and gluons are confined inside the hadrons – 3D structure?

✧ Can we develop analytical tools to connect hadron structure and properties at low energy to the parton description at high energy?!

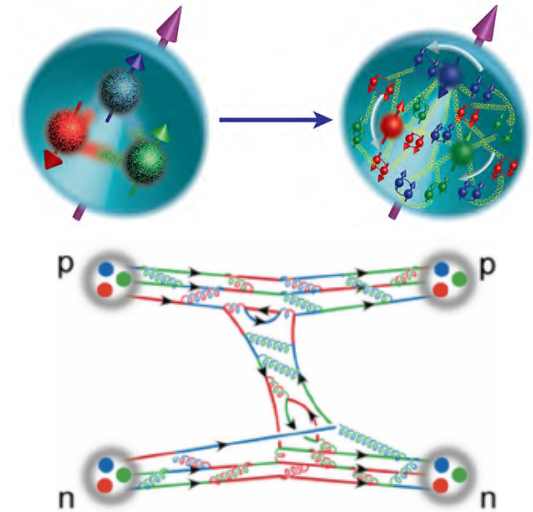
Confined motion, orbital motion, spin,
Quark radius vs proton radius,
Nuclear force from QCD, ...

✧ Can lattice QCD and EFT help?

❑ How does the glue fill out hadron's inner space – 3D glue distribution?

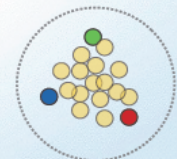
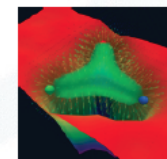
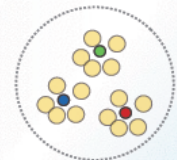
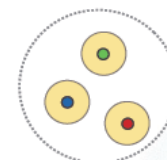
✧ Can we develop better probes to go beyond the current accuracy?!

Gluon radius vs proton radius,
QCD vs QED,
Initial condition for HI collision,
The physics and role of the “x”, ...



Static

Boosted

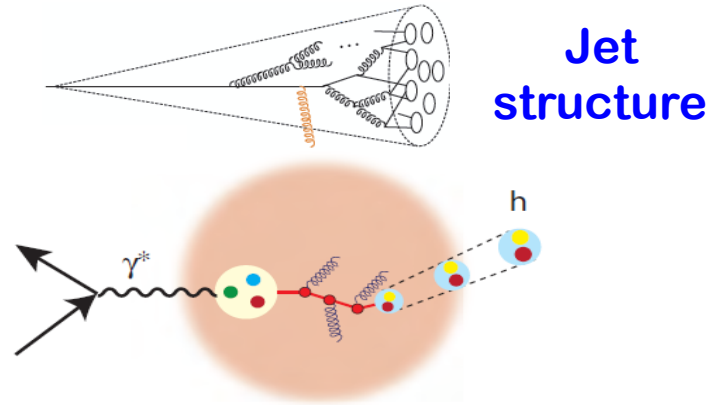


“Big” questions/puzzles about QCD (ep + eA)

□ How hadrons are emerged from the color charge(s)?

- ✧ Can we develop analytical tools to “see” the evolution of the color/jet and to predict the jet structure and the emergence of hadrons?!

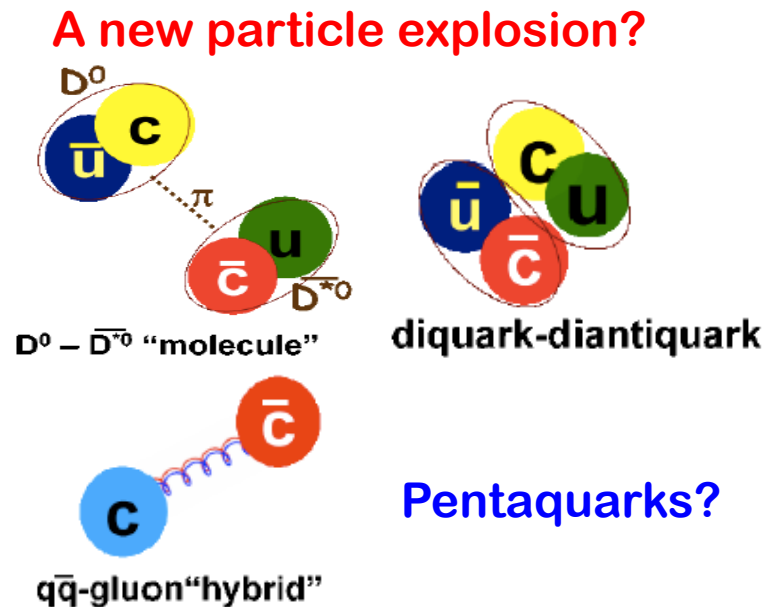
Control of the partonic kinematics?
Hadronization mechanism?



Nucleus as a “vertex detector”
at a femtometer scale

□ How to understand the family of hadrons?

- ✧ Can we see gluonic excitations in hadron spectrum?
- ✧ Interpretations of GlueX data from JLab, precisions?
- ✧ XYZ particles at future ep + eA, ...



Nucleon Structure

□ 1933: Proton's magnetic moment



Otto Stern



1943

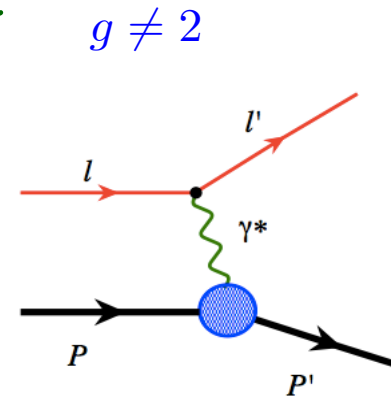
□ 1960: Elastic e-p scattering



Robert Hofstadter

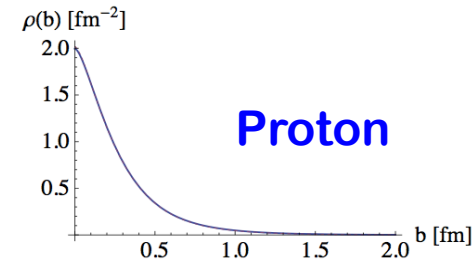


1961

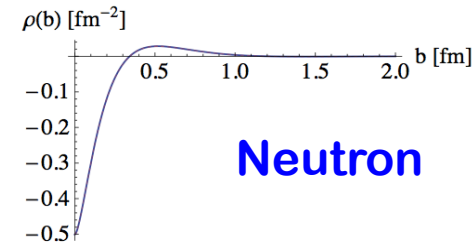


Form factors:

→ Proton "radius" – charge radius

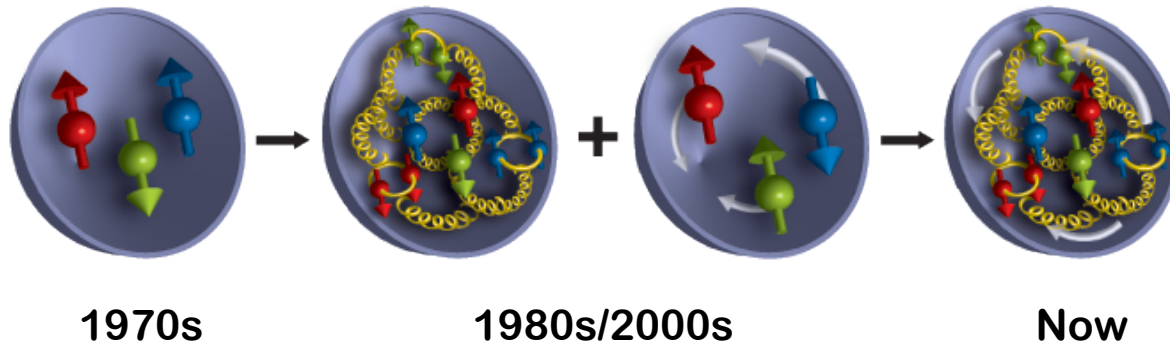


Proton



Neutron

□ Our understanding of the nucleon evolves



1970s

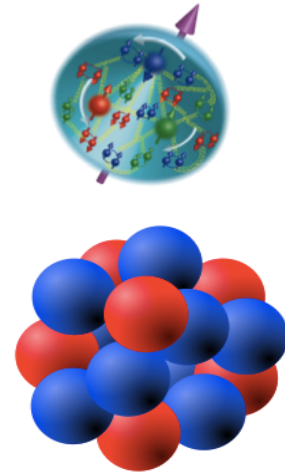
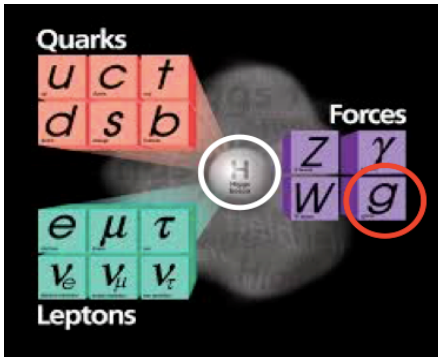
1980s/2000s

Now

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

What holds it together?

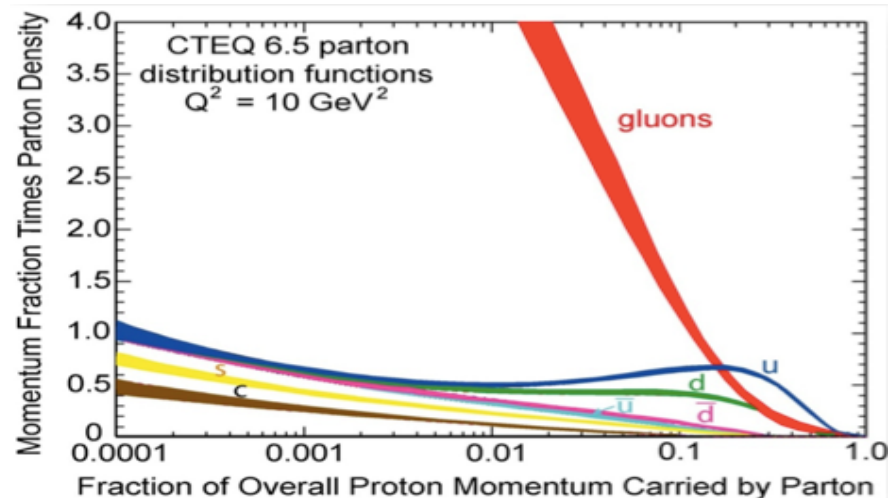
□ Understanding the glue that binds us all – the Next QCD Frontier!



□ Gluons are wired particles!

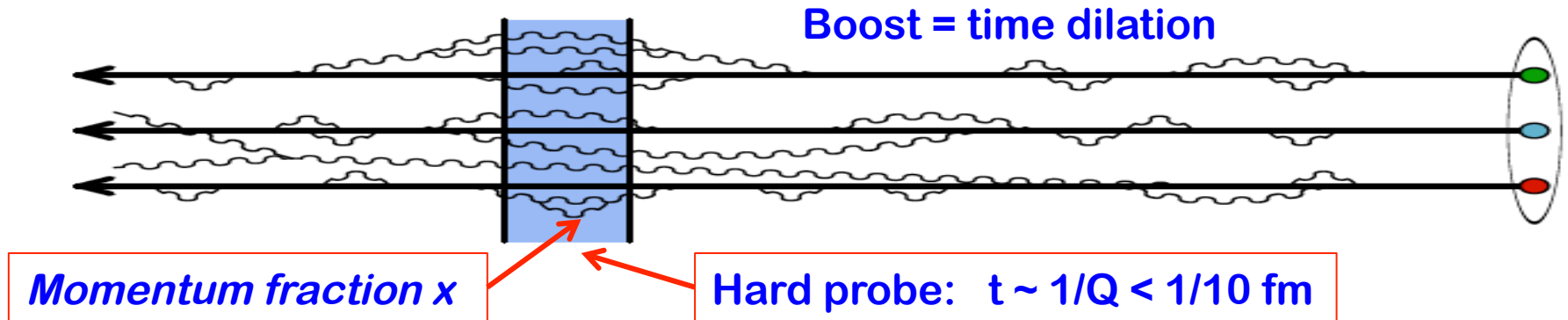
- ✧ Massless, yet, responsible for nearly all visible mass
- ✧ Carry color charge, responsible for color confinement and strong force but, also for asymptotic freedom, as well as the abundance of glue

*Without gluons, there would be
no nucleons, no atomic nuclei...
no visible world!*



Boosted nucleon structure

□ High energy probes “see” the boosted partonic structure:

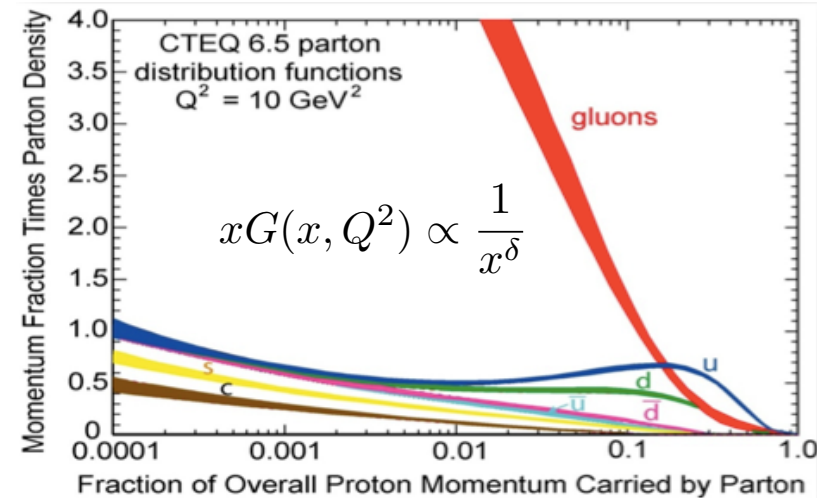


QCD – gluon in a proton:

$$Q^2 \frac{d}{dQ^2} xG(x, Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x', Q^2)$$

QED – photon in a positronium:

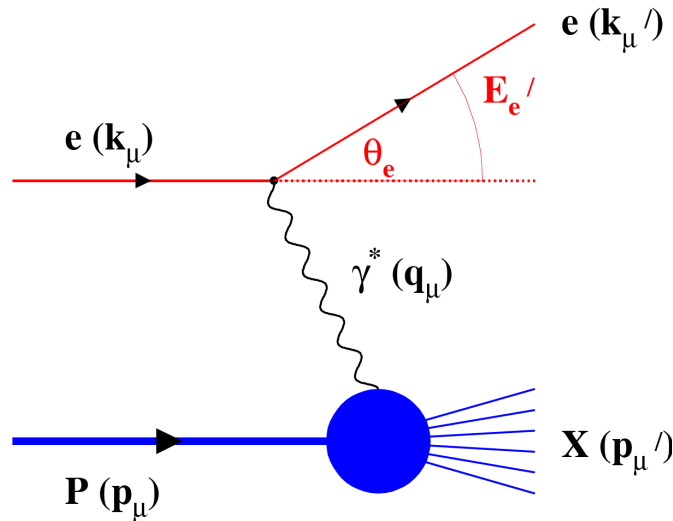
$$Q^2 \frac{d}{dQ^2} x\phi_\gamma(x, Q^2) \approx \frac{\alpha_{em}}{\pi} \left[-\frac{2}{3} x\phi_\gamma(x, Q^2) + \int_x^1 \frac{dx'}{x'} x' [\phi_{e^+}(x', Q^2) + \phi_{e^-}(x', Q^2)] \right]$$



- ✧ At very small- x , proton is “black”, while the positronium is still transparent!
- ✧ Recombination of the large numbers of glue leads to the saturation
 - a universal property of QCD and its gluon self-interaction!

What could learn in next 10 years or so?

□ Lepton-hadron facility: JLab12, COMPASS, ...



$Q^2 \rightarrow$ Measure of resolution

$y \rightarrow$ Measure of inelasticity

$x \rightarrow$ Measure of momentum fraction
of the struck quark in a proton

$$Q^2 = S \times y$$

Inclusive events: $e+p/A \rightarrow e'+X$

Detect only the scattered lepton in the detector

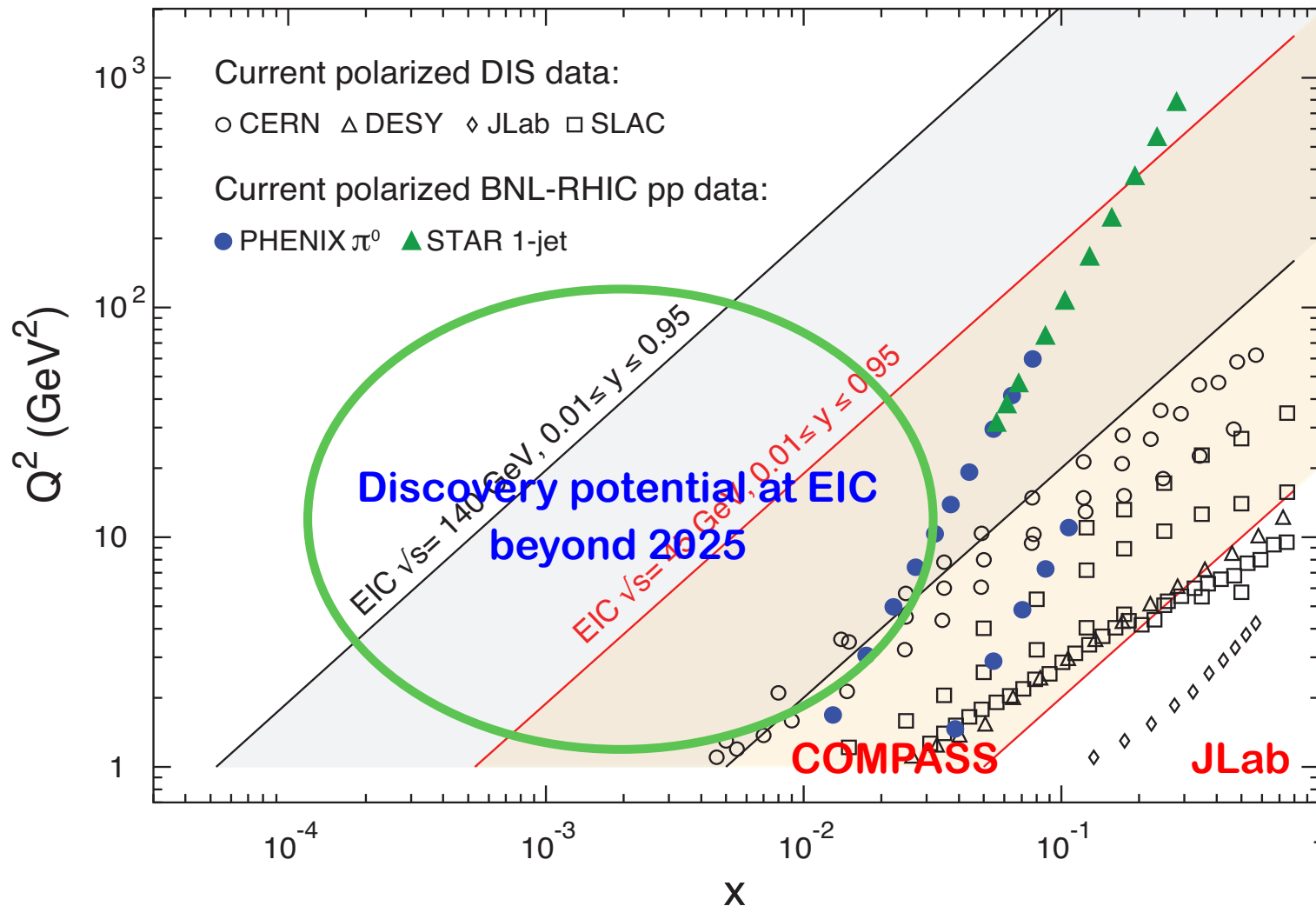
Semi-Inclusive events: $e+p/A \rightarrow e'+h(\pi, K, p, \text{jet})+X$

Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive events: $e+p/A \rightarrow e'+p'/A'+h(\pi, K, p, \text{jet})$

Detect every things including scattered proton/nucleus (or its fragments)

Kinematic coverage (ep)



JLab12 – Valence, COMPASS – Sea quarks, EIC – Sea quarks + Gluons

Hadron structure at large x

□ Testing ground for hadron structure at $x \rightarrow 1$:

✧ $d/u \rightarrow 1/2$

SU(6) Spin-flavor
symmetry

✧ $d/u \rightarrow 0$

Scalar diquark
dominance

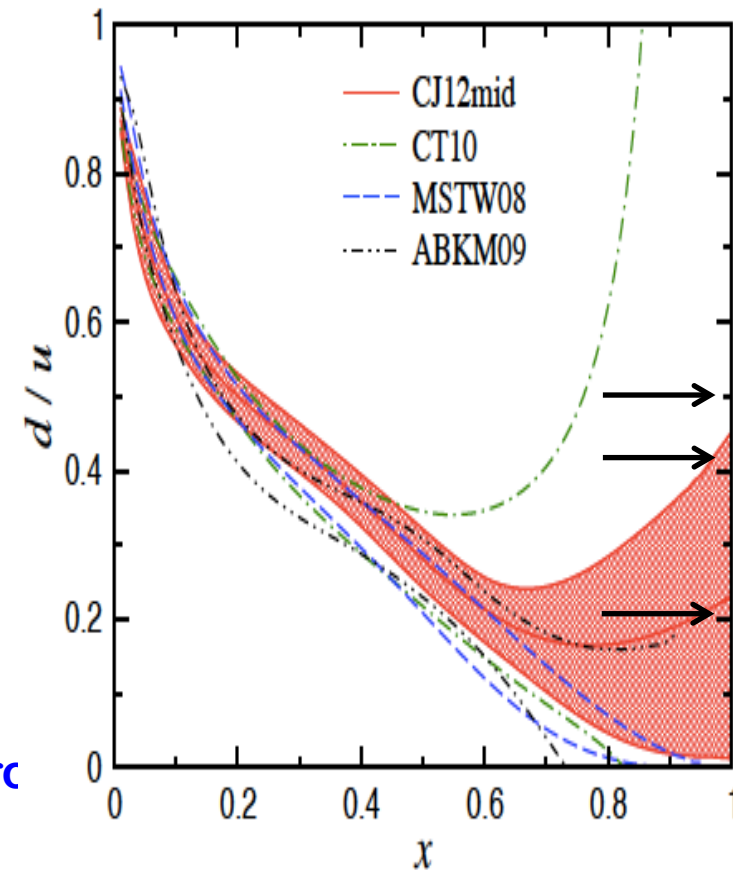
✧ $d/u \rightarrow 1/5$

pQCD power
counting

✧ $d/u \rightarrow \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2}$

Local quark-hadron
duality

≈ 0.42



Hadron structure at large x

□ Testing ground for hadron structure at $x \rightarrow 1$:

$$\diamond d/u \rightarrow 1/2$$

SU(6) Spin-flavor
symmetry

$$\diamond \Delta u/u \rightarrow 2/3$$
$$\Delta d/d \rightarrow -1/3$$

$$\diamond d/u \rightarrow 0$$

Scalar diquark
dominance

$$\diamond \Delta u/u \rightarrow 1$$
$$\Delta d/d \rightarrow -1/3$$

$$\diamond d/u \rightarrow 1/5$$

pQCD power
counting

$$\diamond \Delta u/u \rightarrow 1$$
$$\Delta d/d \rightarrow 1$$

$$\diamond d/u \rightarrow \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2}$$
$$\approx 0.42$$

Local quark-hadron
duality

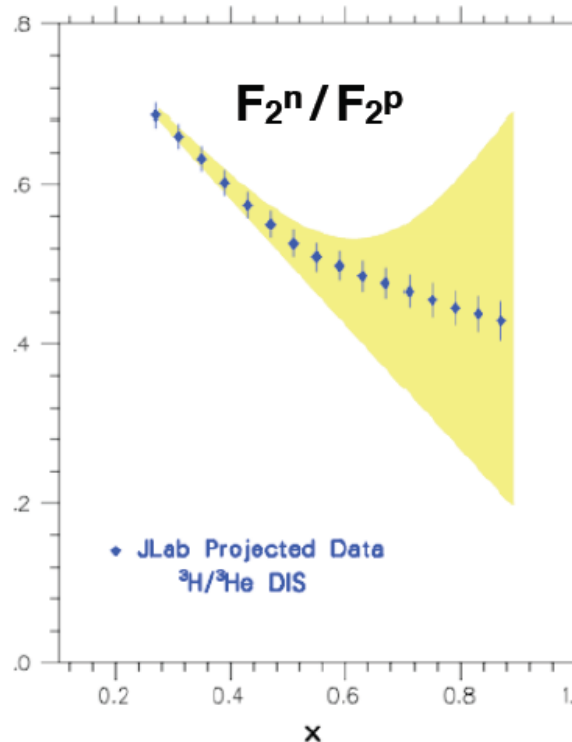
$$\diamond \Delta u/u \rightarrow 1$$
$$\Delta d/d \rightarrow 1$$

Can lattice QCD help?

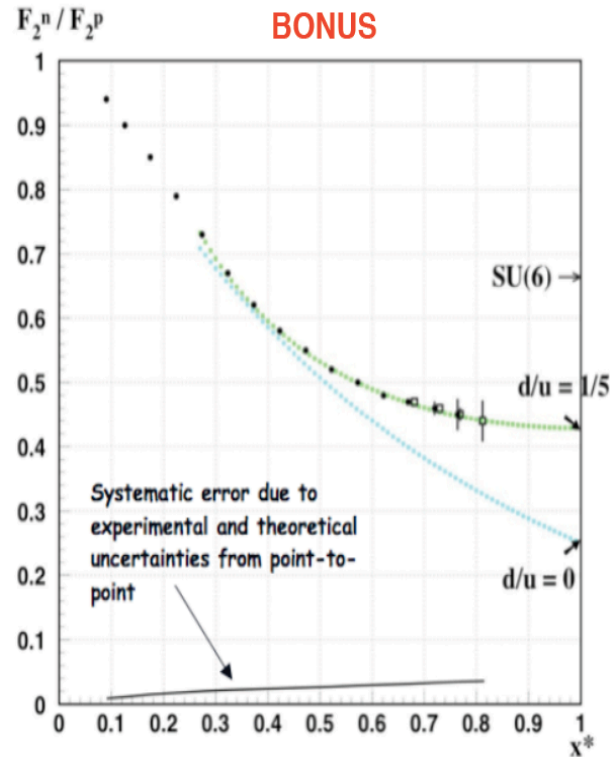
Upcoming experiments – JLab12

□ NSAC milestone HP14 (2018):

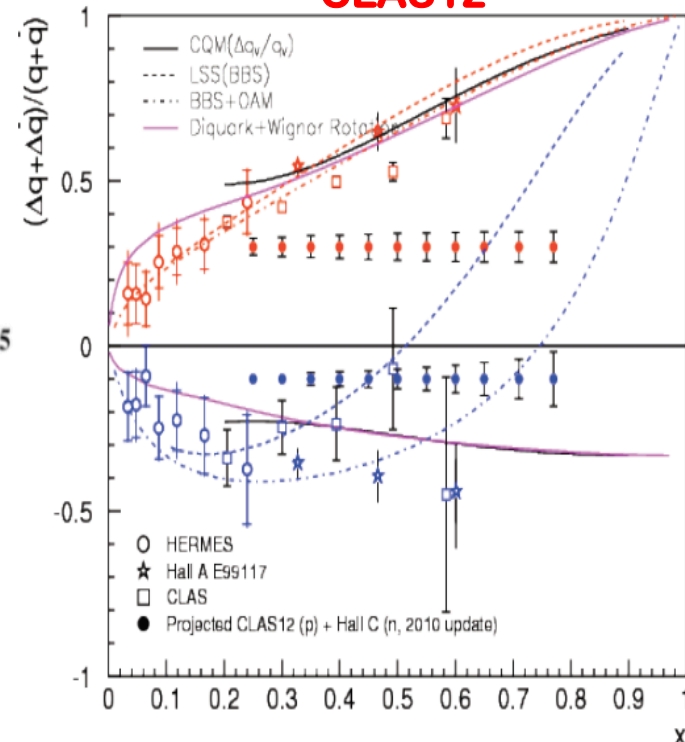
MARATHON



BONUS



CLAS12



Plus many more JLab experiments:

E12-06-110 (Hall C on ^3He), E12-06-122 (Hall A on ^3He),

E12-06-109 (CLAS on NH_3 , ND_3), ...

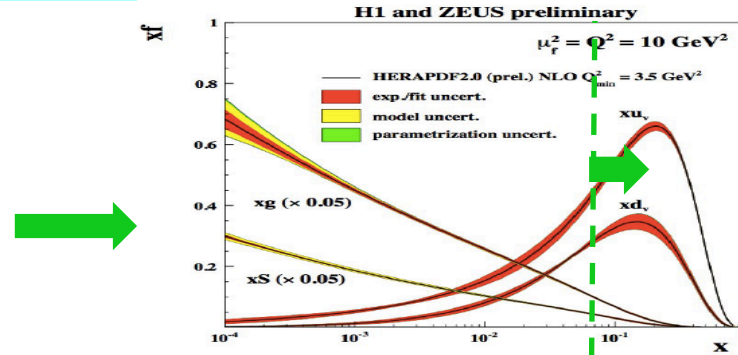
and Fermilab E906, ...

Plus complementary Lattice QCD effort

Lattice calculations of hadron structure



Lattice QCD



X-dep distributions

See also
Lin's talk

□ New ideas – from quasi-PDFs (lattice calculable) to PDFs:

✧ High P_z effective field theory approach:

$$\tilde{q}(x, \mu^2, P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y}, \frac{\mu}{P_z}\right) q(y, \mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2}, \frac{M^2}{P_z^2}\right)$$

Ji, et al.,
arXiv:1305.1539
1404.6680

✧ QCD collinear factorization approach:

$$\tilde{q}(x, \mu^2, P_z) = \sum_f \int_0^1 \frac{dy}{y} C_f\left(\frac{x}{y}, \frac{\mu^2}{\bar{\mu}^2}, P_z\right) f(y, \bar{\mu}^2) + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

Ma and Qiu,
arXiv:1404.6860
1412.2688
Ishikawa, Qiu, Yoshida,

Parameter
like \sqrt{s}

Factorization
scale

High twist
Power corrections

□ Open issues – major progresses by 2025:

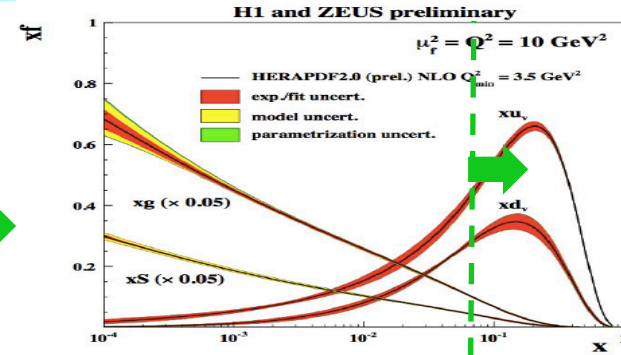
The TMD Collaboration

Proton state with a large P_z on lattice, non-perturbative UV renormalization, ..

Lattice calculations of hadron structure



Lattice QCD



X-dep distributions

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□ New ideas – from quasi-PDFs (lattice calculable) to PDFs:

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Ma and Qiu,
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1412.2688
Ishikawa, Qiu, Yoshida,

Parameter
like \sqrt{s}

Factorization
scale

High twist
Power corrections

□ Tremendous potentials:

The TMD Collaboration

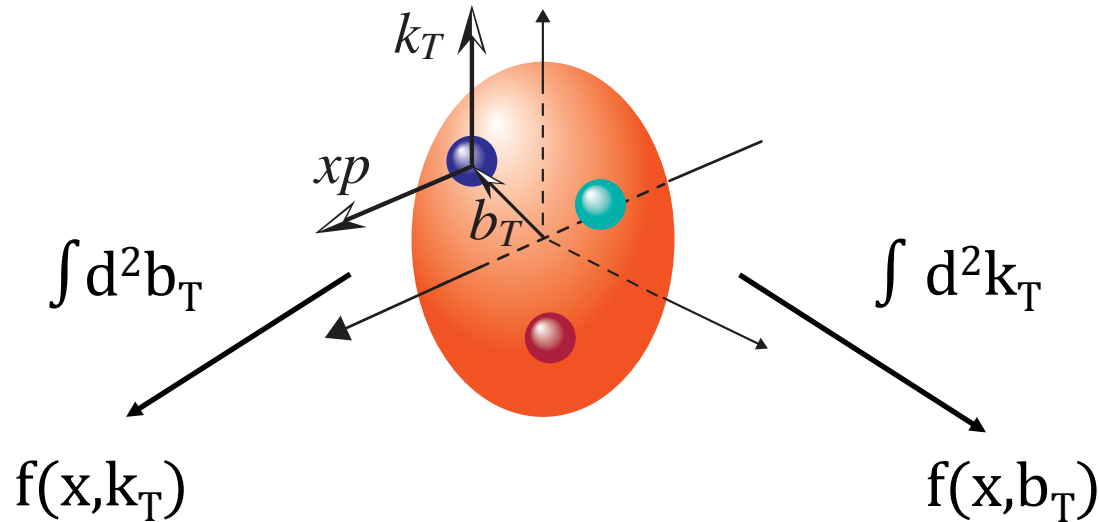
PDFs of proton, neutron, pion, ..., TMDs, GPDs, ... – the TMD Collaboration

Boosted 3D nucleon structure

□ High energy probes “see” the boosted partonic structure:

*Momentum
Space*

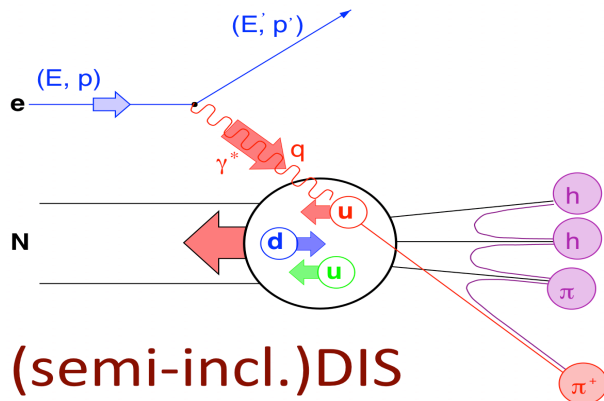
TMDs



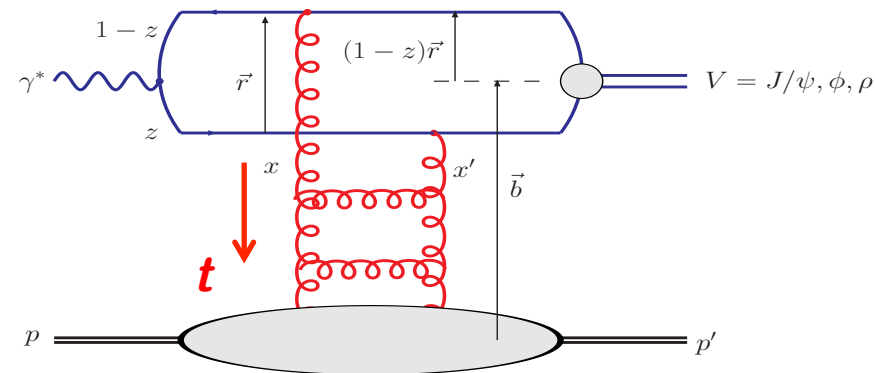
*Coordinate
Space*

GPDs

3D momentum space images



2+1D coordinate space images

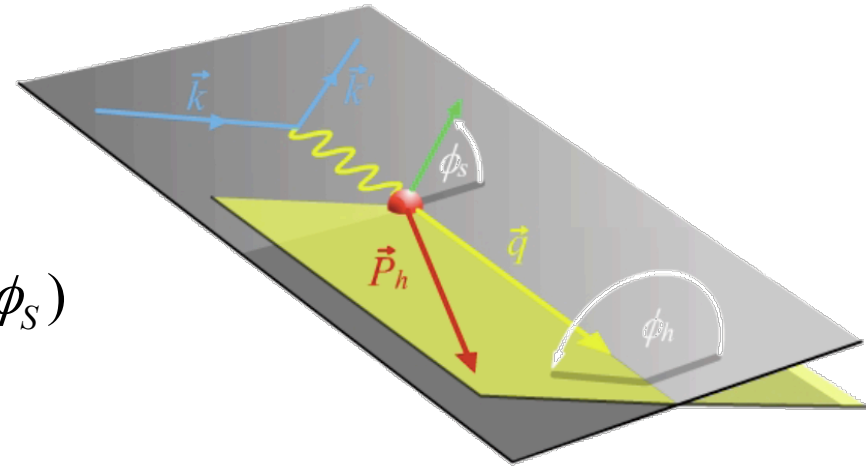


Major parts of JLab12's physics program – large x

SIDIS is the best for probing TMDs

□ Naturally, two planes:

$$\begin{aligned}
 A_{UT}(\varphi_h^l, \varphi_S^l) &= \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \\
 &= A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_S) \\
 &\quad + A_{UT}^{\text{Pretzelosity}} \sin(3\phi_h - \phi_S)
 \end{aligned}$$



□ Separation of TMDs:

$$A_{UT}^{\text{Collins}} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{\text{Sivers}} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{\text{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

← Collins frag. Func.
from e^+e^- collisions



Hard, if not impossible, to separate TMDs in hadronic collisions

Using a combination of different observables (not the same observable):
jet, identified hadron, photon, ...

Modified universality for TMDs

□ Parity – Time reversal invariance:



$$f_{q/h\uparrow}^{\text{SIDIS}}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h\uparrow}^{\text{DY}}(x, \mathbf{k}_\perp, -\vec{S})$$

□ Definition of Sivers function:

$$f_{q/h\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{2} \Delta^N f_{q/h\uparrow}(x, k_\perp) \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp$$

□ Modified universality:

$$\Delta^N f_{q/h\uparrow}^{\text{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h\uparrow}^{\text{DY}}(x, k_\perp)$$

Same function, but, opposite sign!

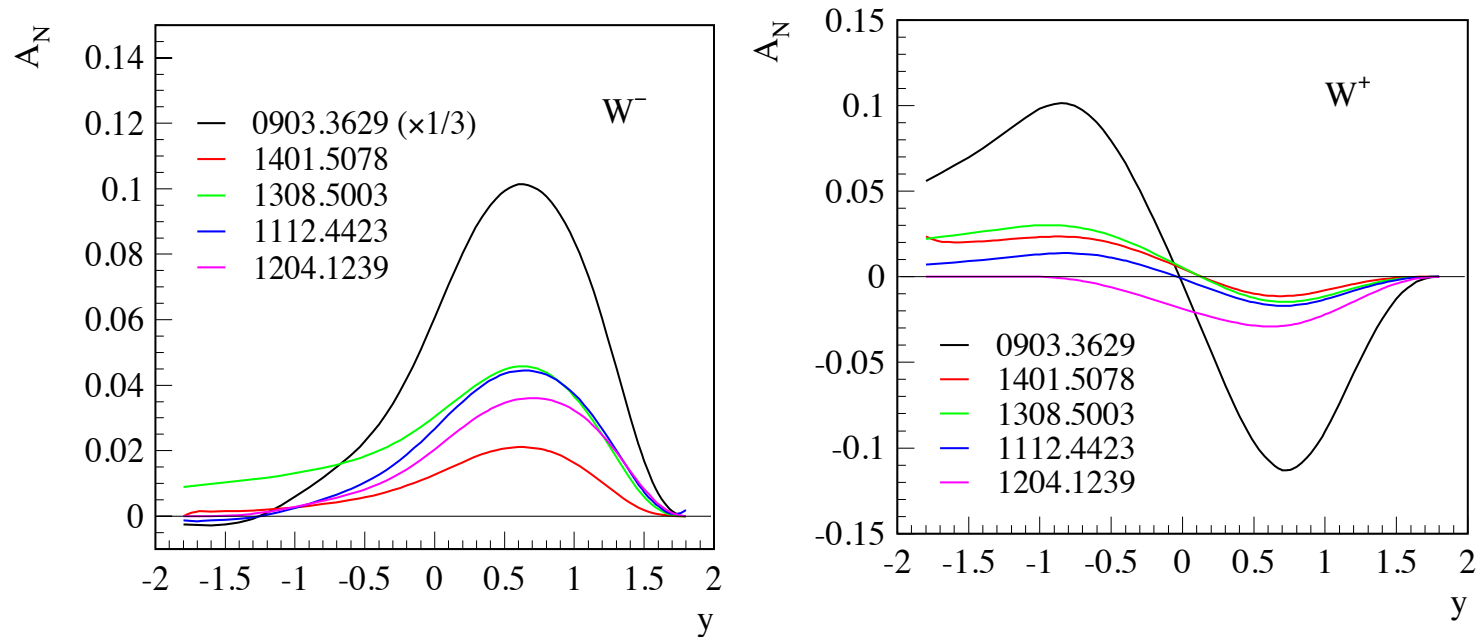
□ The sign change = Critical test of TMD factorization!

Same applies to TMD gluon distribution

COMPASS – DY, FNAL – DY, RHIC – W/Z+DY program, ...

Boosted 3D nucleon structure

□ Current “predictions” and uncertainty of QCD evolution:



□ Coordinated theory effort is needed:

- ✧ **TMD Topical Collaboration: Lattice, theory & Phenomenology**
- ✧ **The evolution and the sign change are solvable problems!**
- ✧ **RHIC is the excellent and unique facility to test this (W/Z – DY)!**



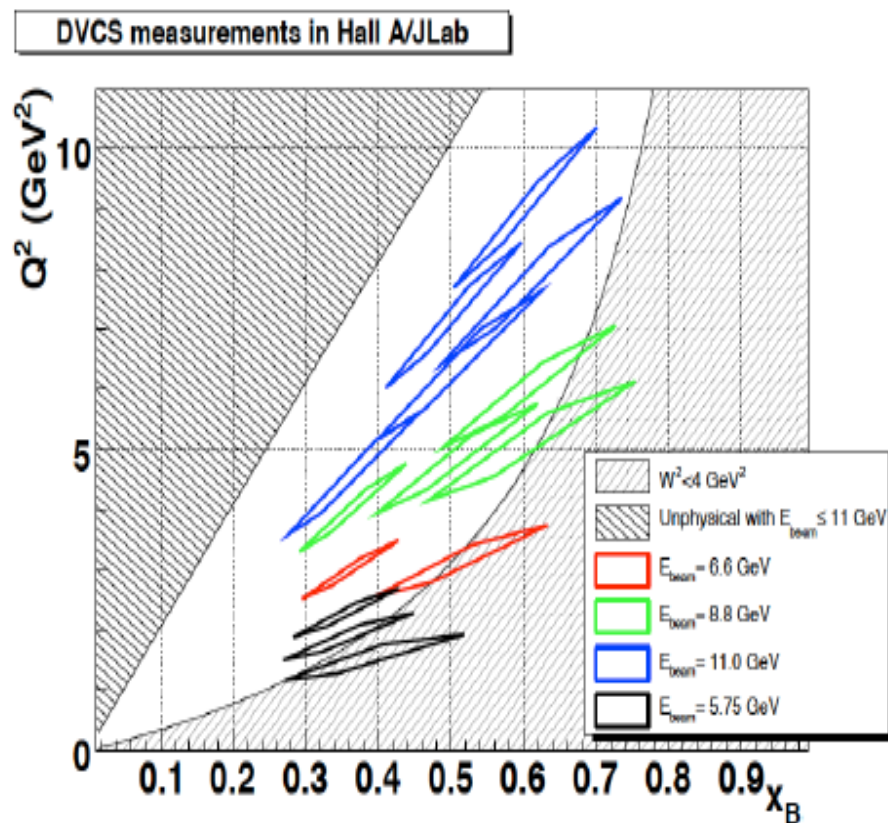
Controlled probes for the 3D confined motion by 2025!

Quark/gluon transverse profile

□ DVCS at JLab12

✧ Establish scaling of σ_{DVCS} in Hall A

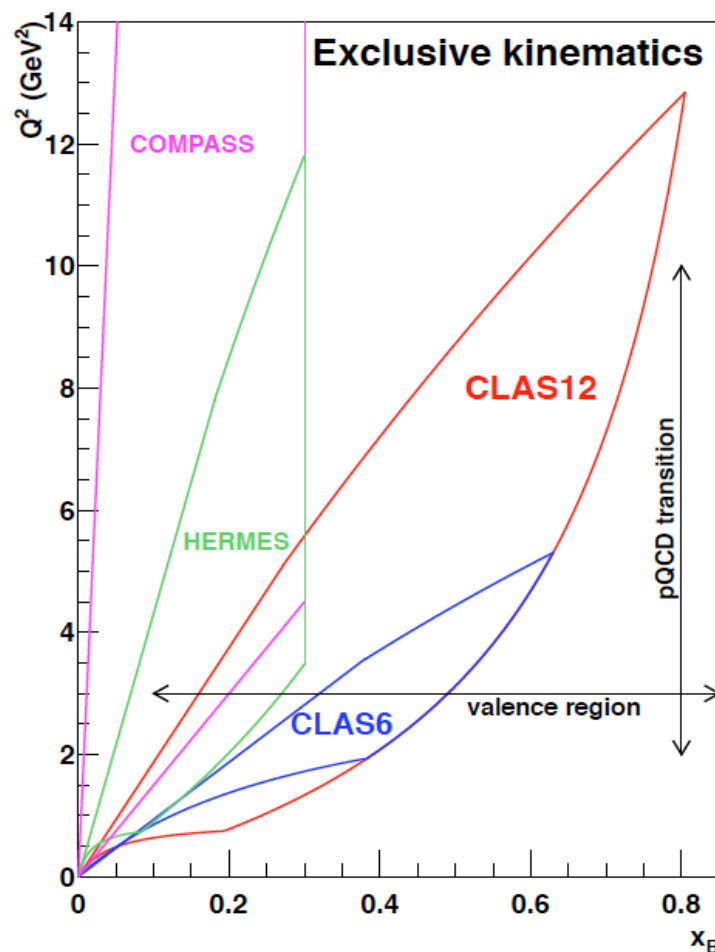
Run earlier



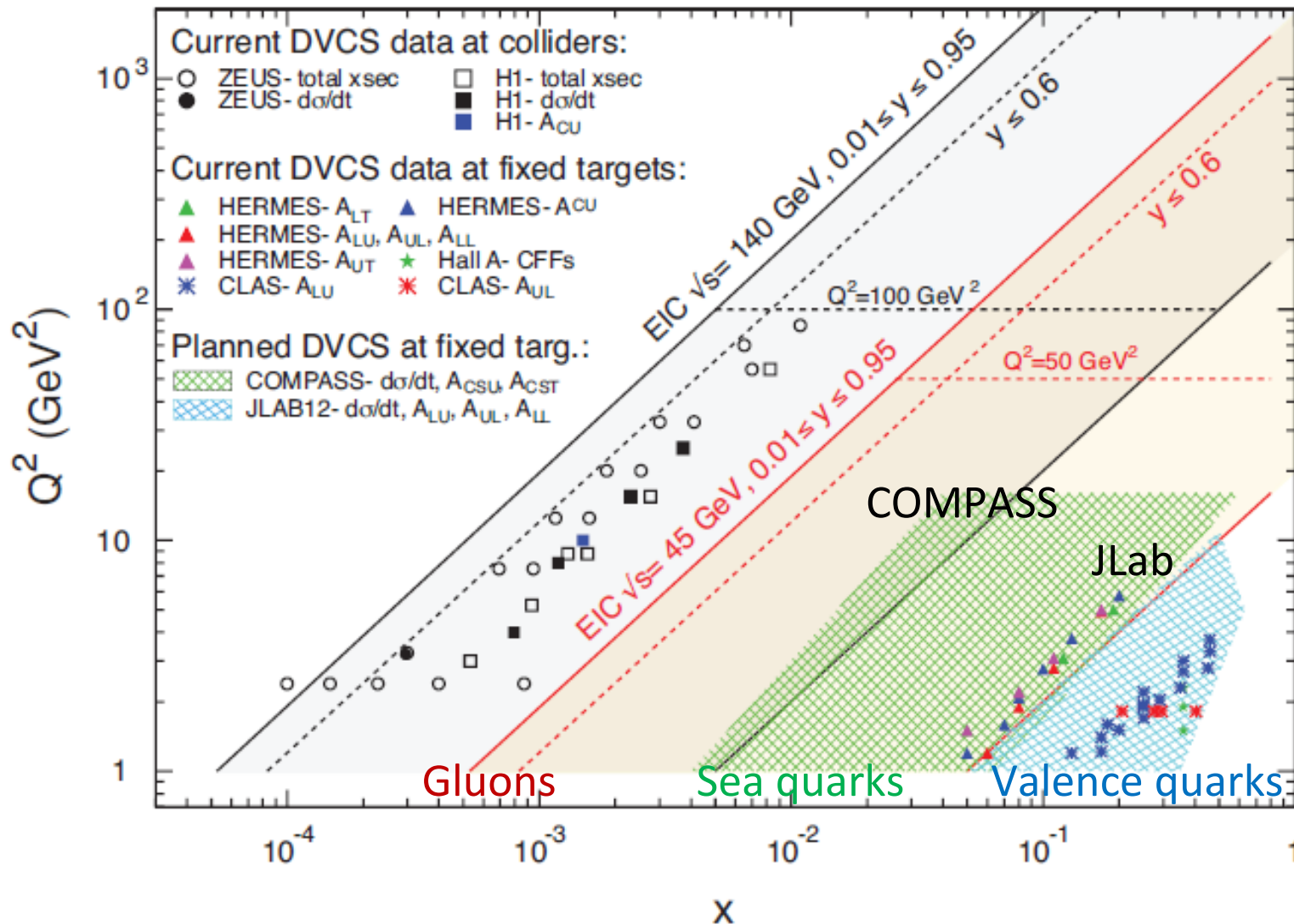
Theory: global fitting to extract GPDs

✧ Measure DVCS at CLAS

broad kinematic range with polarized & unpol observables



JLab + COMPASS coverage for GPDs



EIC: a new generation of lepton-hadron collider is needed!

Boosted 3D nucleon structure

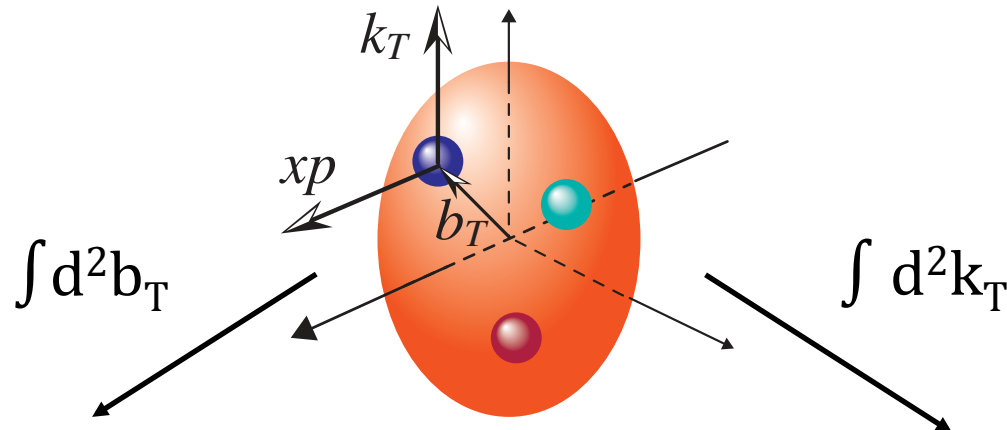
□ High energy probes “see” the boosted partonic structure:

*Momentum
Space*

TMDs

*Coordinate
Space*

GPDs



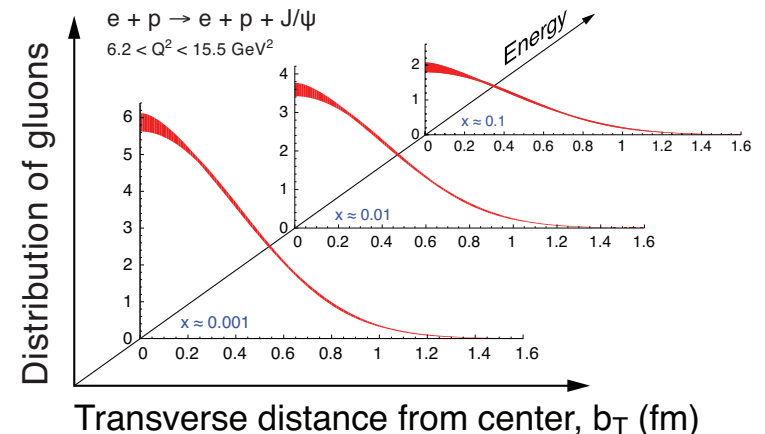
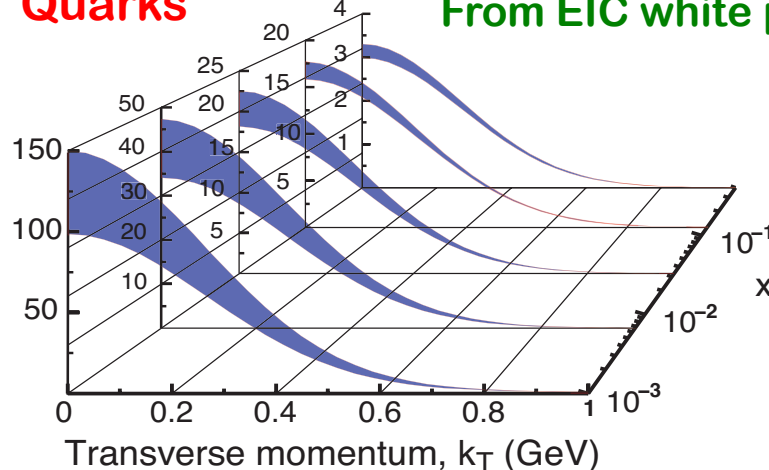
$f(x, k_T)$

$f(x, b_T)$

Quarks

From EIC white paper: arXiv:1212.1701

Gluons



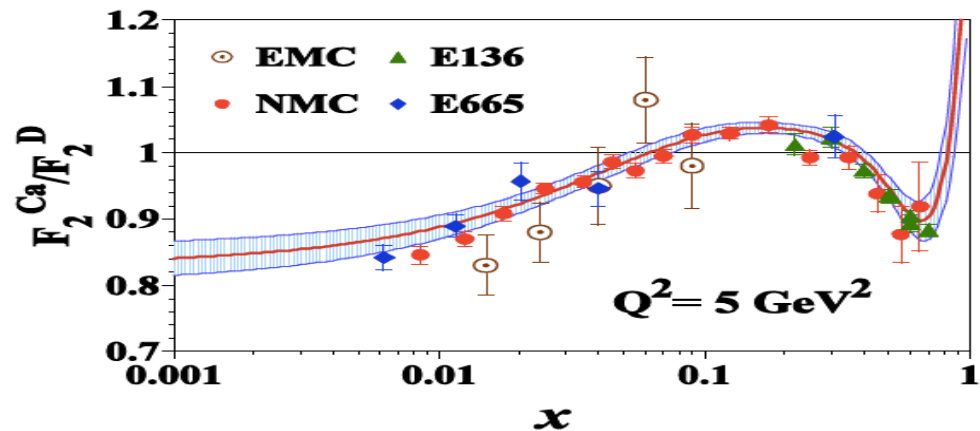
Not discussed: various hadron form factors at JLab12

Nuclear landscape?

□ EMC discovery:

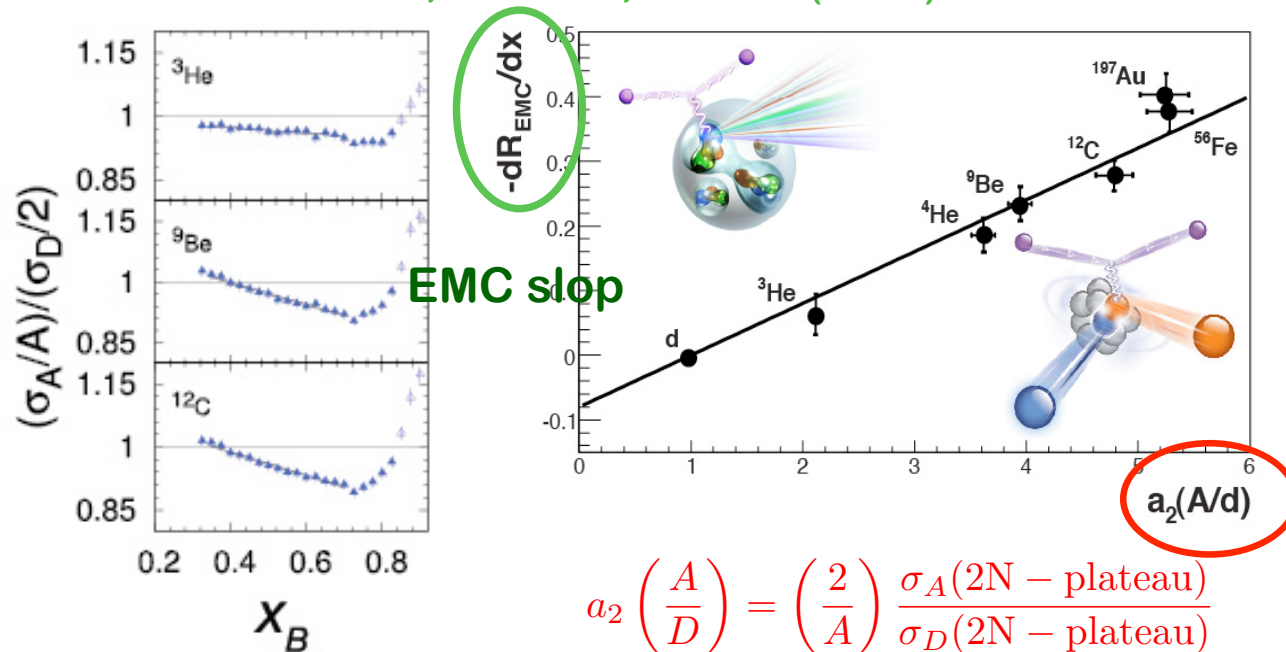
Nuclear landscape

≠ superposition
of nucleon landscape



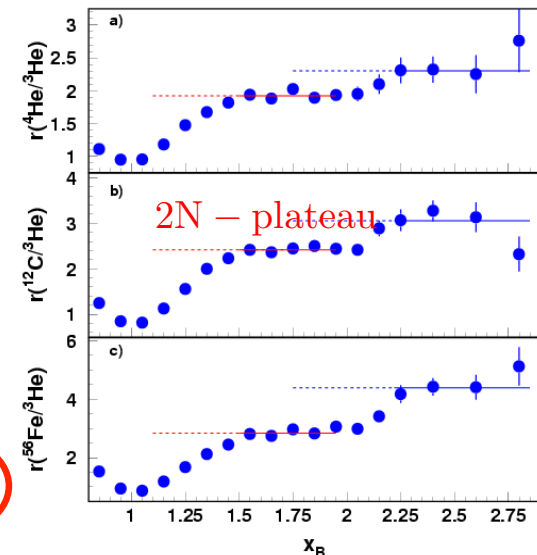
□ JLab12 measurement of EMC effect and beyond:

Weinstein et al., PRL 106, 052301 (2011)



$$a_2 \left(\frac{A}{D} \right) = \left(\frac{2}{A} \right) \frac{\sigma_A(2N - \text{plateau})}{\sigma_D(2N - \text{plateau})}$$

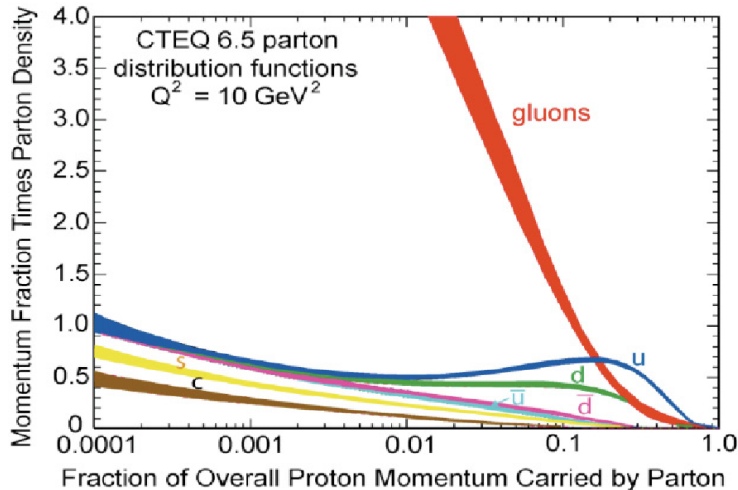
SRC



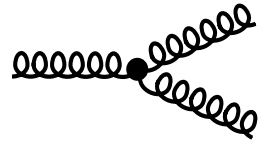
Cloet et al.

Run away gluon density at small x?

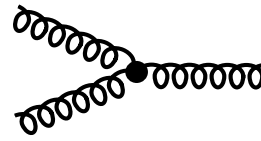
HERA discovery:



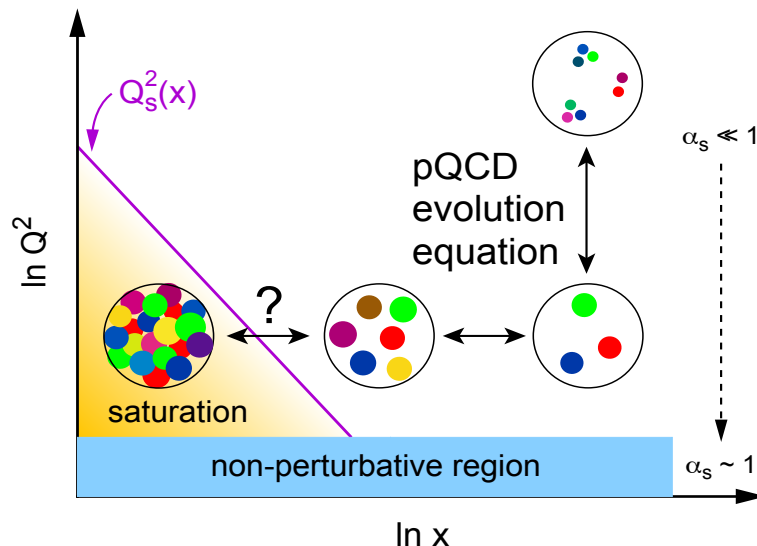
What causes the low-x rise?
gluon radiation
– non-linear gluon interaction



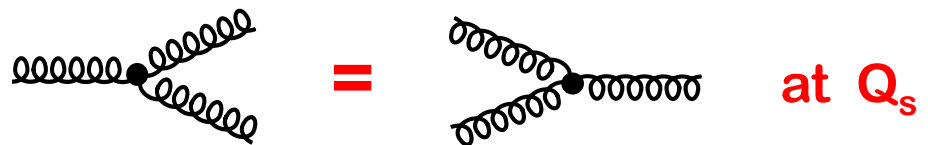
What tames the low-x rise?
gluon recombination
– non-linear gluon interaction



Particle vs. wave feature:



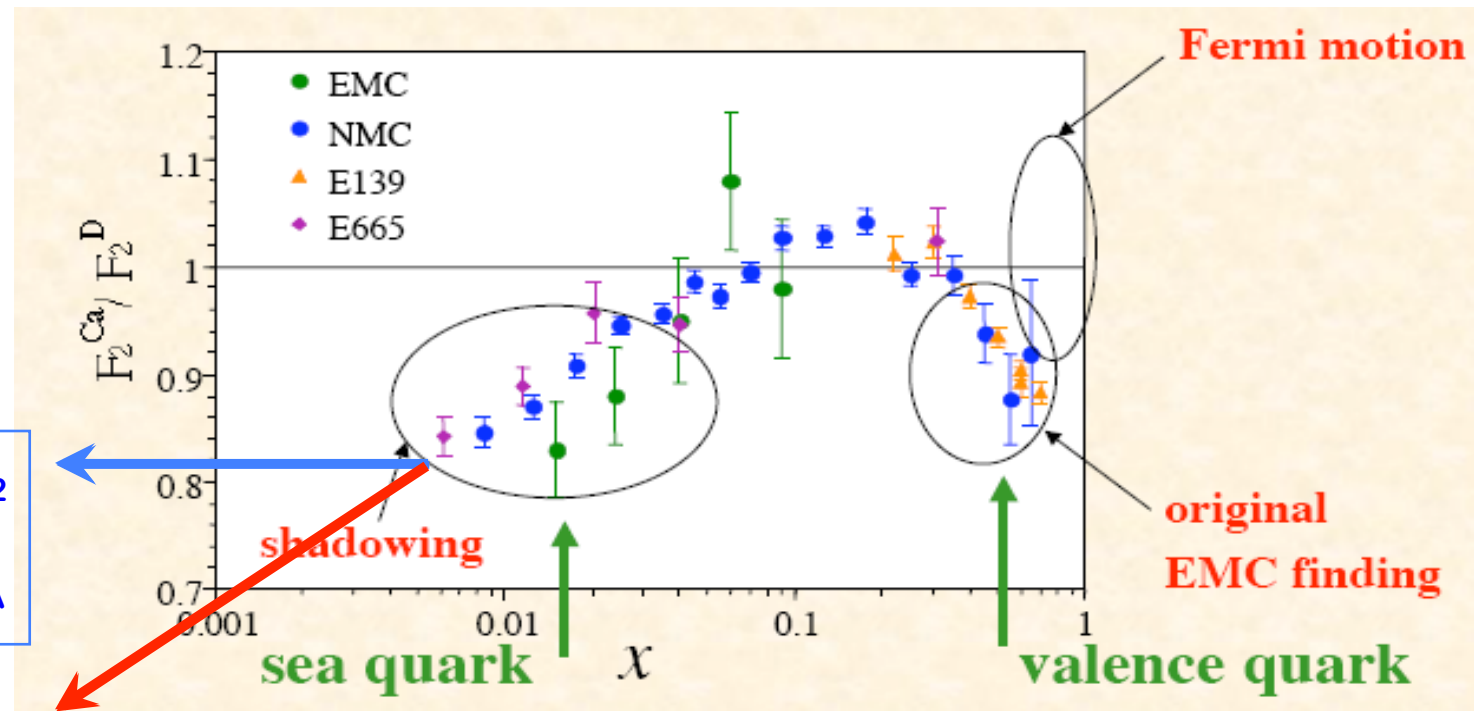
Gluon saturation – Color Glass Condensate
radiation = recombination



*Leading to a collective gluonic system?
with a universal property?
new effective theory QCD – CGC?*

An “easiest” measurement

□ EMC effect, Shadowing and Saturation:



□ Questions:

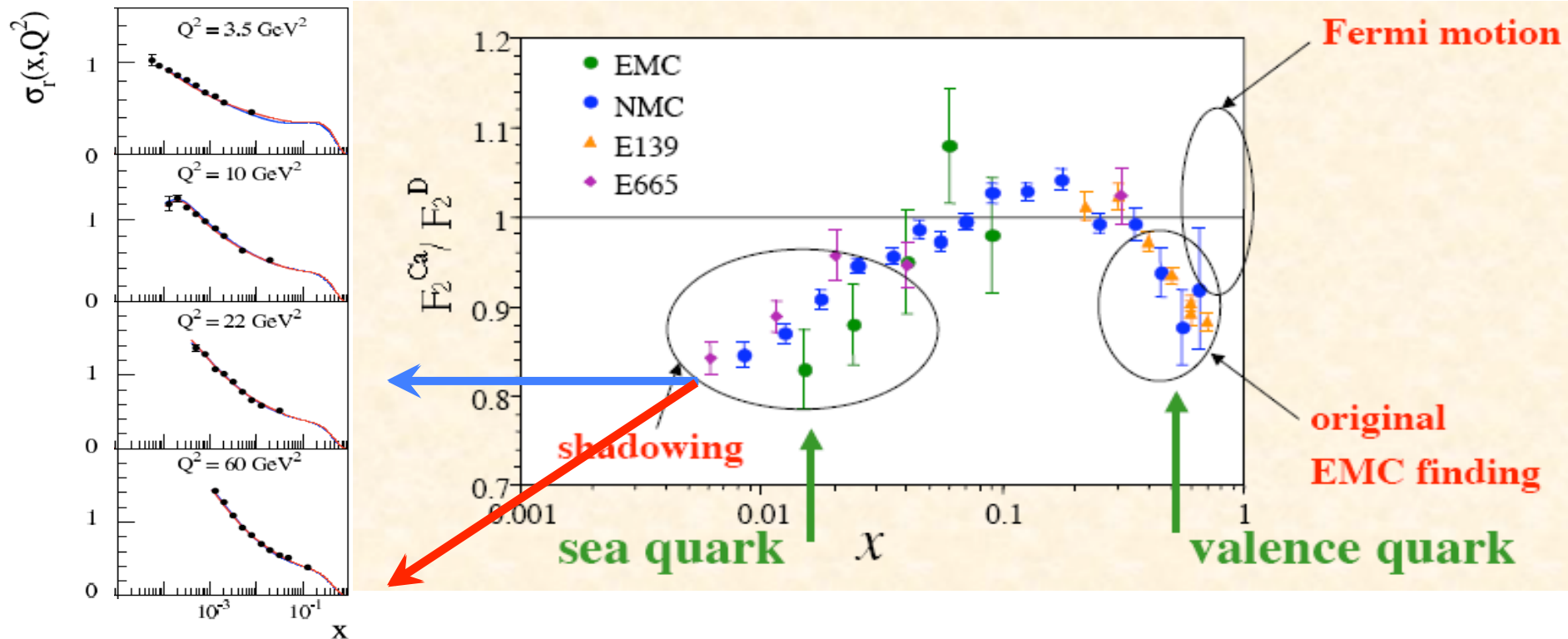
Will the suppression/shadowing continue fall as x decreases?

Could nucleus behaves as a large proton at small- x ?

Range of color correlation – could impact the center of neutron stars!

An “easiest” measurement

□ EMC effect, Shadowing and Saturation:



□ Questions:

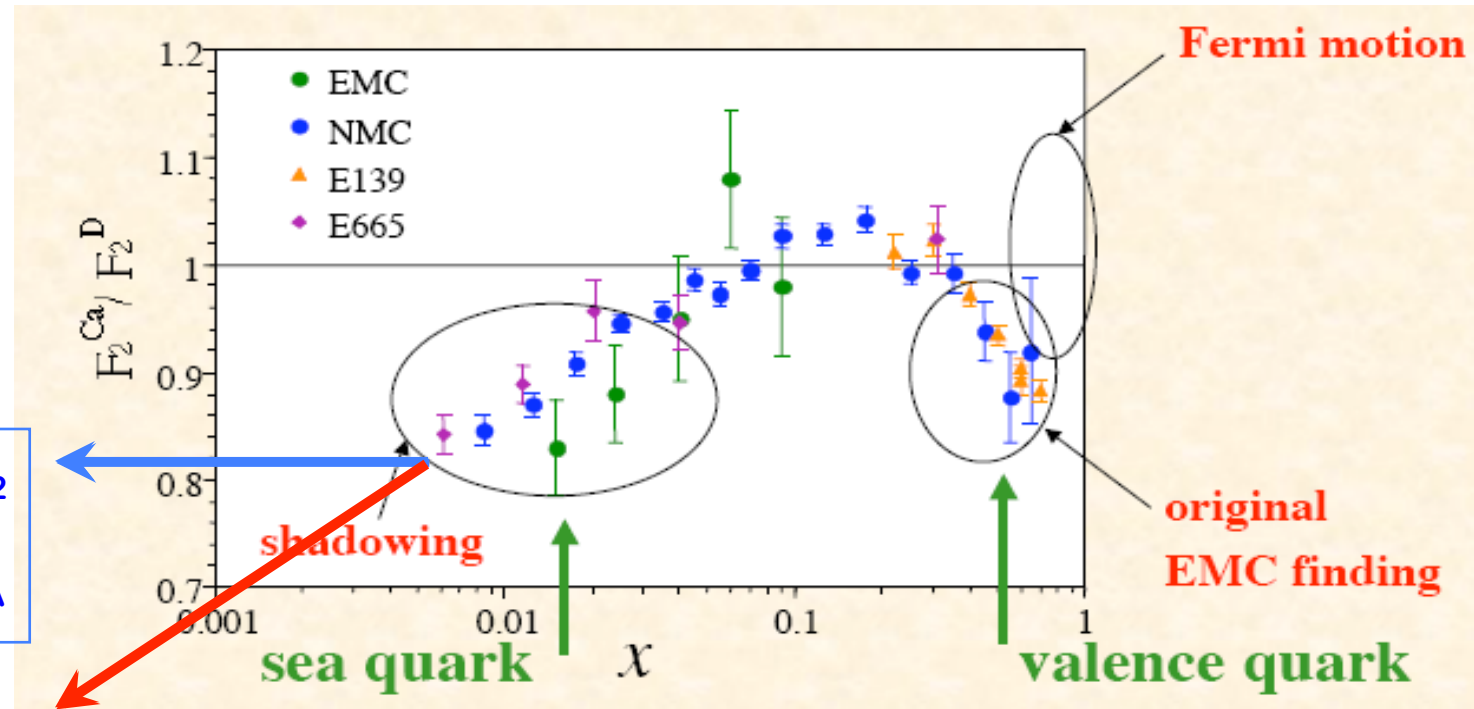
Will the suppression/shadowing continue fall as x decreases?

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Range of color correlation – could impact the center of neutron stars!

An “easiest” measurement

❑ EMC effect, Shadowing and Saturation:



Saturation in R_{F_2}
 \neq
Saturation in F_2^A

Saturation in $F_2(A) = R_{F_2}$ decreases until saturation in $F_2(D)$

❑ Questions:

Will the suppression/shadowing continue fall as x decreases?

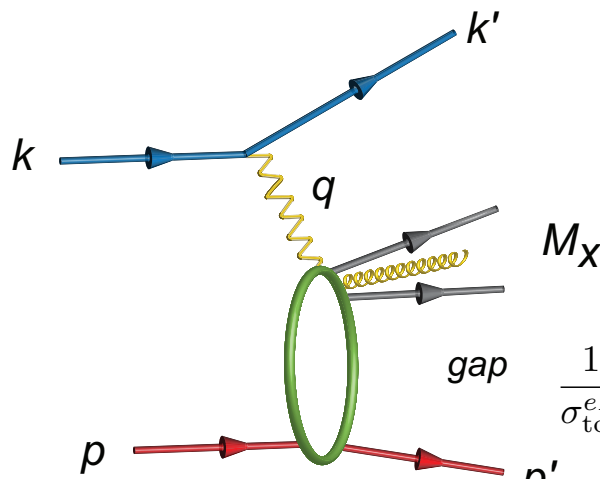
Could nucleus behaves as a large proton at small-x?

Range of color correlation – could impact the center of neutron stars!

The best signature for gluon saturation

□ Diffractive cross section:

$$\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$$



$$\frac{1}{\sigma_{\text{tot}}^{eA}} \frac{d\sigma_{\text{diff}}^{eA}}{dM_x^2} \bigg/ \frac{1}{\sigma_{\text{tot}}^{ep}} \frac{d\sigma_{\text{diff}}^{ep}}{dM_x^2} \sim \frac{25 - 30\%}{10 - 15\%} > 1$$

$$\frac{1}{\sigma_{\text{tot}}^{eA}} \frac{d\sigma_{\text{diff}}^{eA}}{dM_x^2} \bigg/ \frac{1}{\sigma_{\text{tot}}^{ep}} \frac{d\sigma_{\text{diff}}^{ep}}{dM_x^2} \sim \left[\frac{g^p(x)}{g^A(x)} \right]_{\text{tot}} \left[\frac{g^A(x)}{g^p(x)} \right]_{\text{diff}}^2 < 1$$

At HERA

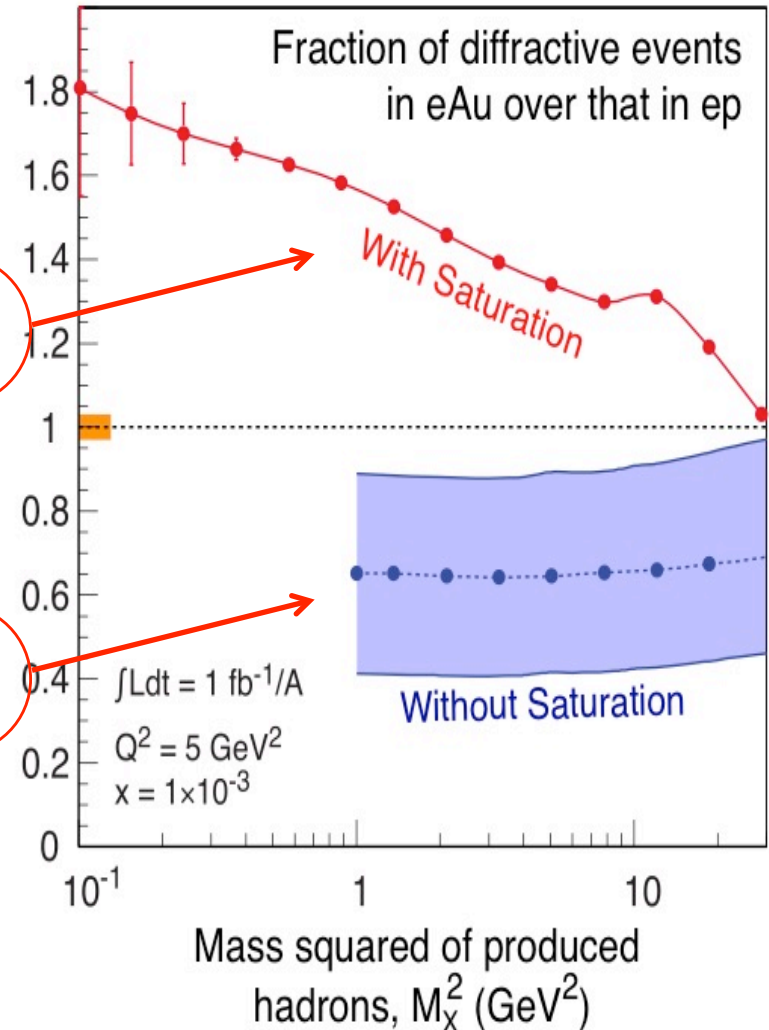
ep: 10-15% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30% diffractive

Early work – E665 @ FNAL:

Nuclear shadowing, diffractive scattering and low momentum protons in μ Xe interactions at 490 GeV



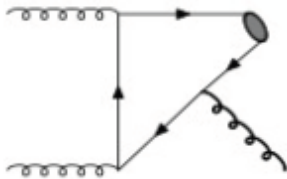
Emergence of hadrons/Jets

□ Hadronization:

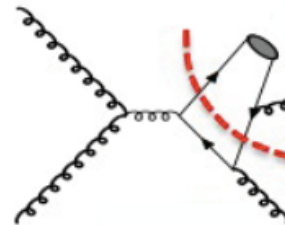
- ✧ Single-Parton Fragmentation functions – necessary for SIDIS
- ✧ Double-Parton Fragmentation functions – new

Heavy quarkonium production - $c\bar{c}$ ($b\bar{b}$) fragmentation
(rate, polarization, hadronization mechanism, ...)

Kang, et al.
Fleming et al.



$$\frac{d\hat{\sigma}^{LO}}{dp_T^2} \approx \alpha_s^3 \frac{m_Q^4}{p_T^8}$$

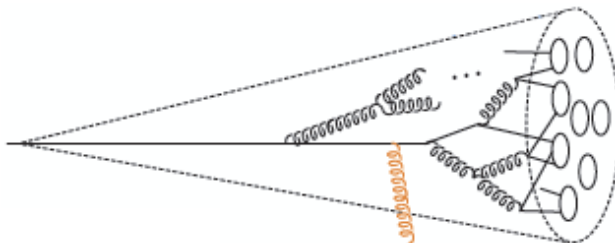


$$\frac{d\hat{\sigma}^{NLO}}{dp_T^2} \approx \alpha_s^4 \frac{m_Q^2}{p_T^6}$$

Light meson production - $u\bar{d}$ ($u\bar{s}$, ...) fragmentation
(suppressed in production, enhanced in fragmentation, ...)

□ Jet substructure:

See also Vitev's talk



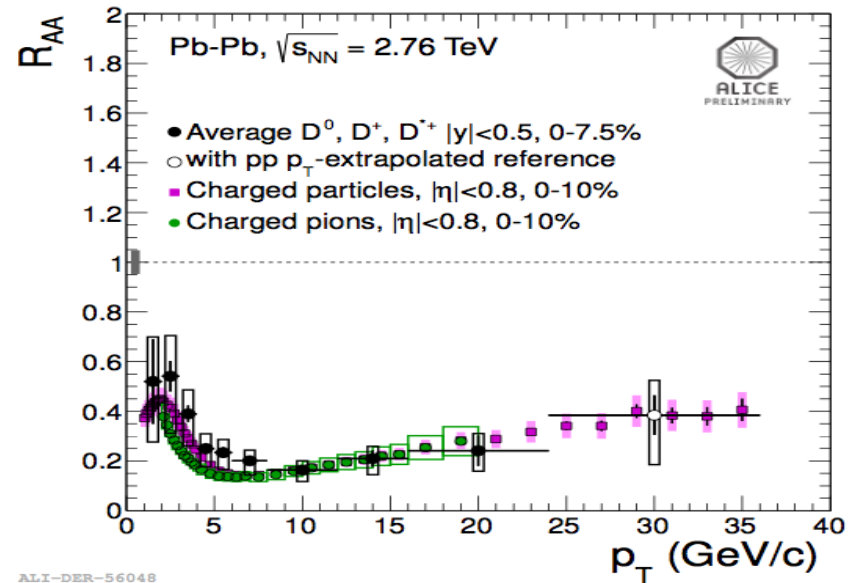
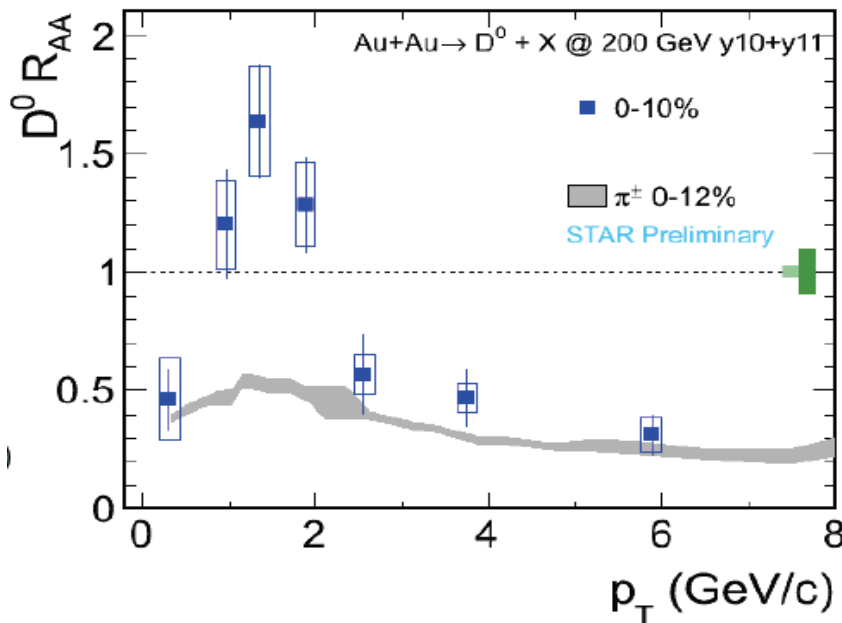
Two-scales: Jet energy \gg Jet “mass”

Tool: Soft-Collinear Effective Theory (SCET)

Challenge: Jet in medium?

Hadronization puzzle

❑ Strong suppression of heavy flavors in AA collisions:



❑ Emergence of hadrons:

How do hadrons emerge from a created quark or gluon?

How is the color of quark or gluon neutralized?

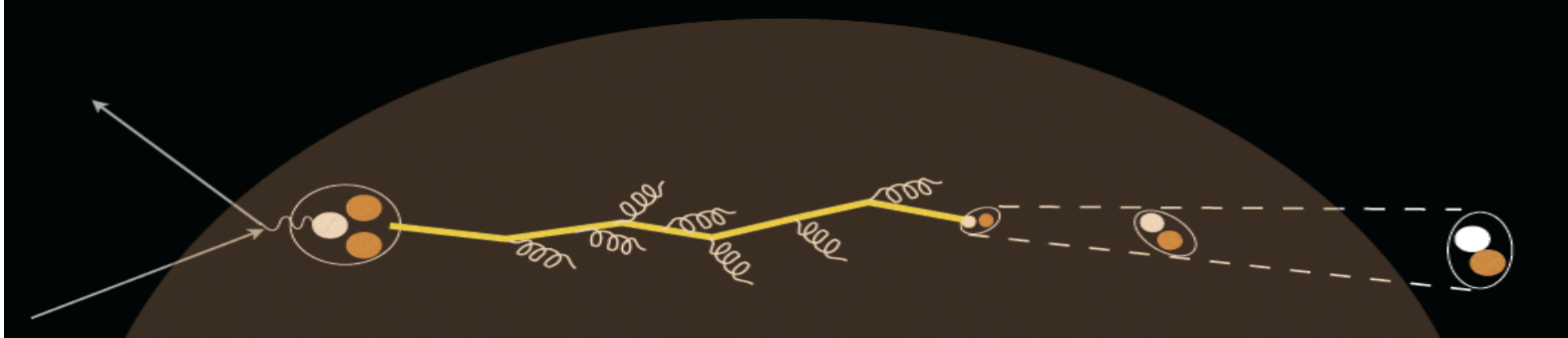
❑ Need a femtometer detector or “scope”:

Nucleus, a laboratory for QCD

Evolution of partonic properties

In-medium hadronization

- Unprecedented range of photon energy ν at EIC: $\nu = \frac{Q^2}{2mx}$



- ✧ Small ν - in medium hadronization:

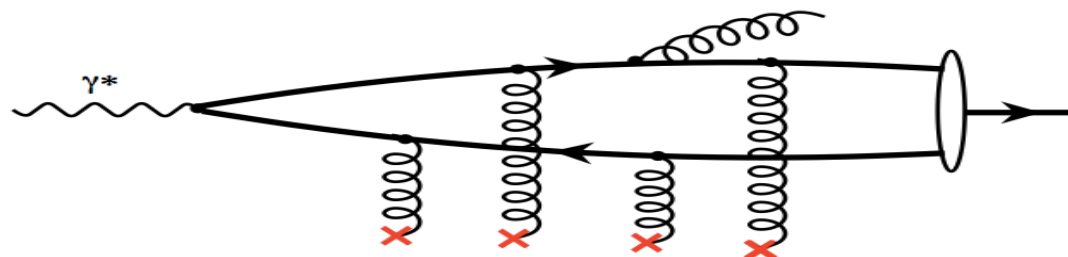
Stages of hadronization: parton, pre-hadron, hadron

- ✧ Large ν - parton multiple scattering:

Parton energy loss – cold nuclear matter \hat{q}

- Heavy quark and quarkonium production:

Nucleus:
Femtometer size
Vertex detector

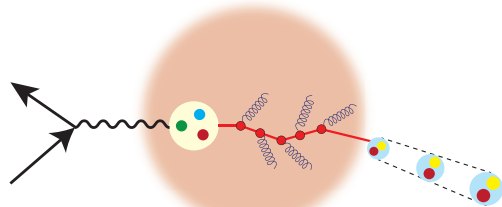


Filter for production
mechanism!

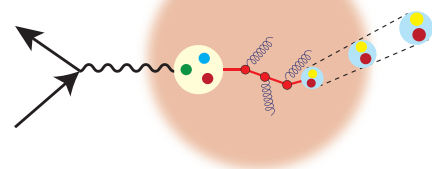
Emergence of hadrons from partons

How hadrons emerge from colored quarks and gluons?

□ Unprecedented ν range at EIC:



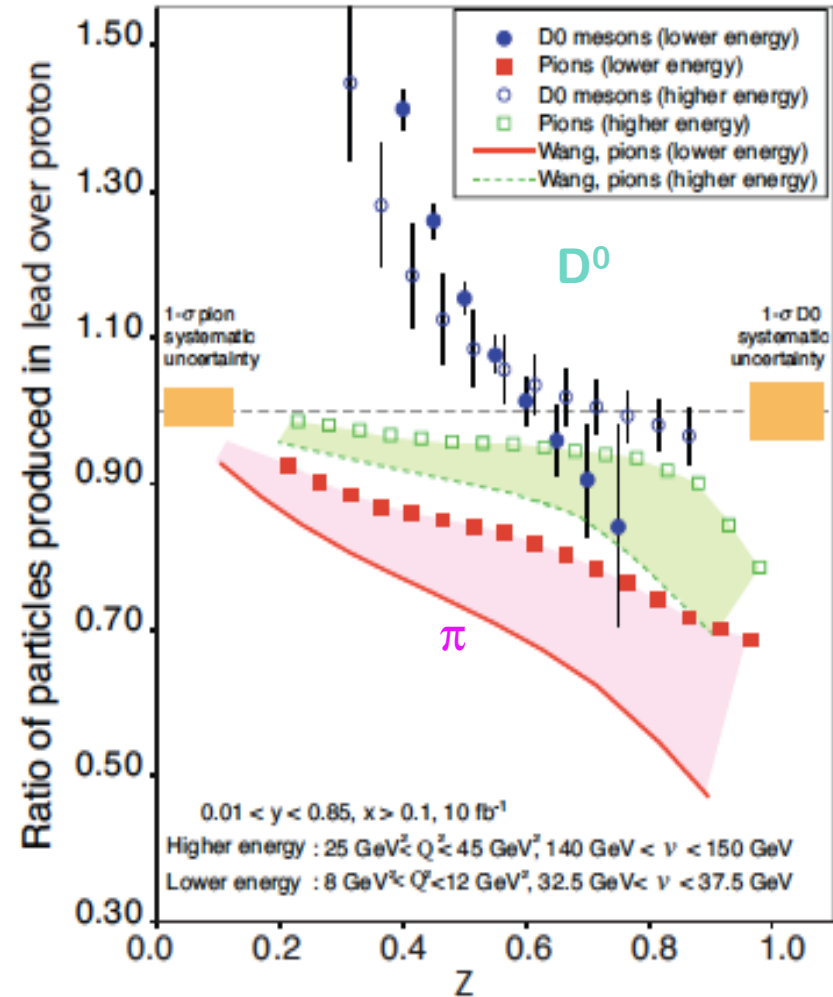
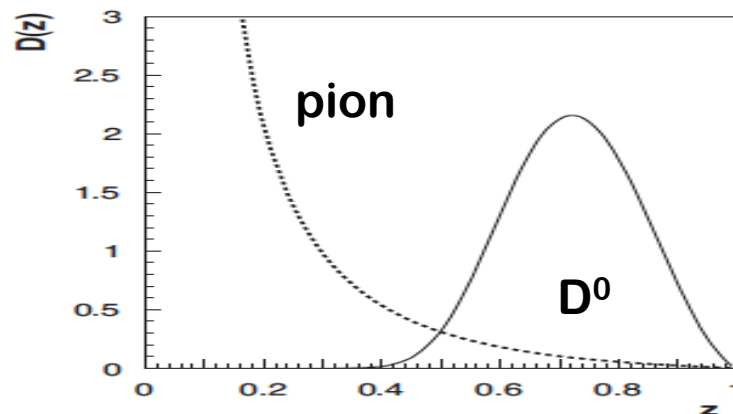
$$\nu = \frac{Q^2}{2mx}$$



Control of ν and medium length!

□ Heavy quark energy loss:

– Mass dependence of fragmentation

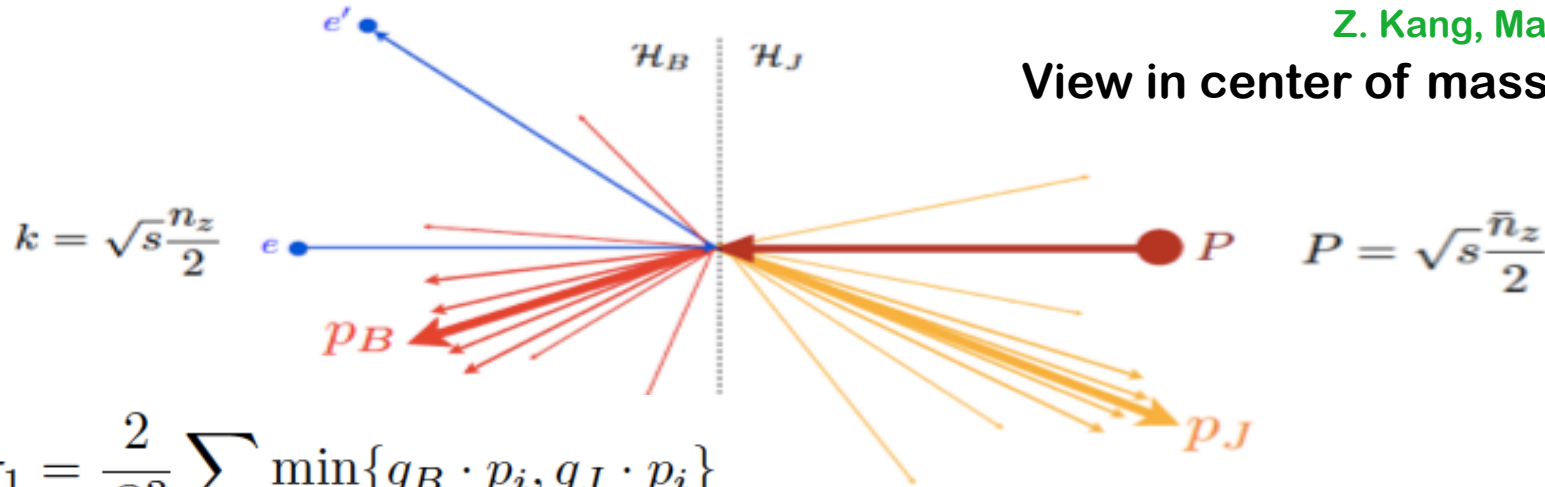


Need the collider energy of EIC and its control on parton kinematics

1-Jettiness cross section in e-A – event shape

Z. Kang, Mantry, Qiu, 2012

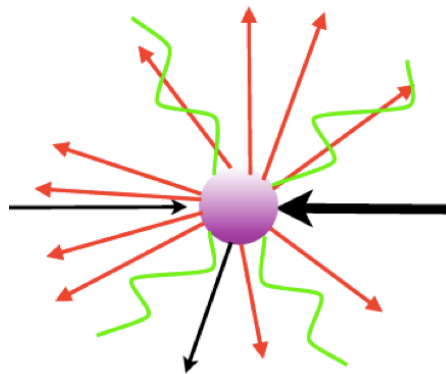
View in center of mass frame



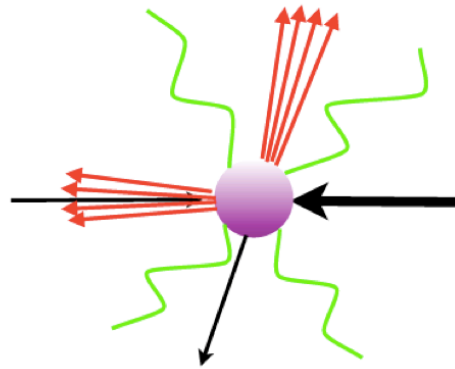
$$\tau_1 = \frac{2}{Q^2} \sum_i \min\{q_B \cdot p_i, q_J \cdot p_i\}$$

$$d\sigma_A \equiv \frac{d^3\sigma(e^- + N_A \rightarrow J + X)}{du dP_{JT} d\tau_1}$$

1-jettiness:
global event
shape



$$\tau_1 \sim P_{JT}$$



$$\tau_1 \ll P_{JT}$$

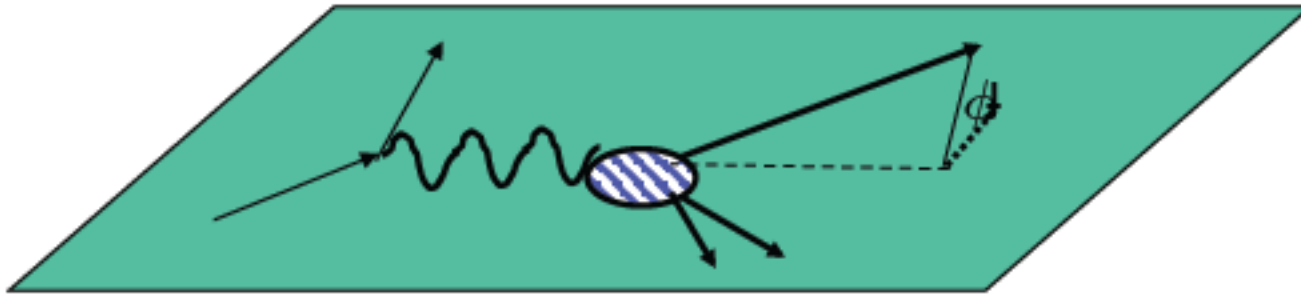
Good measurement
of the radiation pattern

D. Kang, Lee, Stewart, 2013

Density distribution – Fluctuation

□ Azimuthal distribution:

Guo, Liang, Wang, 2010
Pitonyak, Qiu



V_n in SIDIS?

$$\langle \cos \phi \rangle_{eA} = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \frac{k_T}{Q} \frac{x_B f_{A\perp}^q(x_B, k_T)}{f_A^q(x_B, k_T)}$$

□ A-dependence of the k_T -dependent distribution:

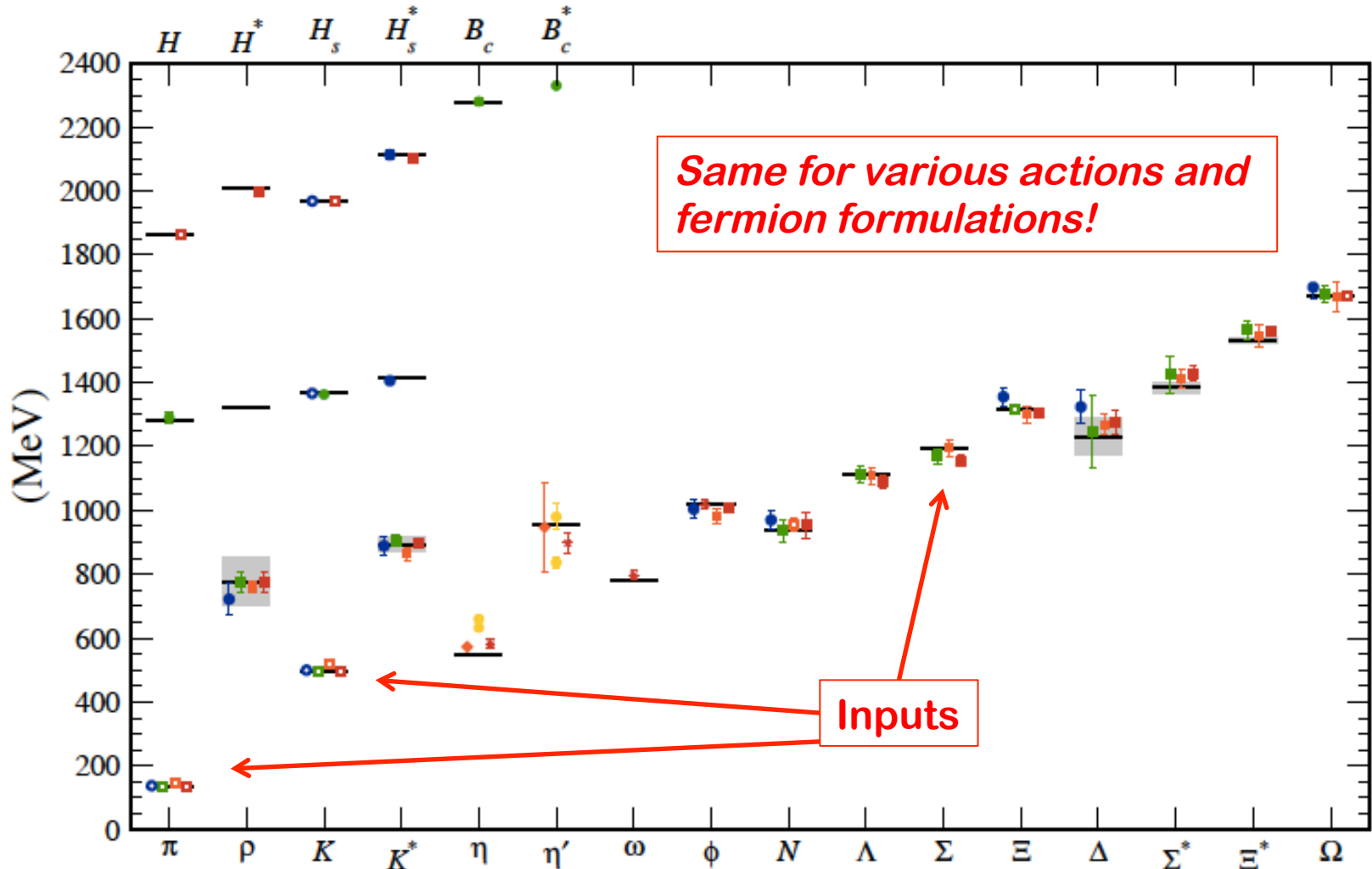
$$f_{A\perp}^q(x, k_T) \approx \left(1 + \frac{\Delta}{2k_T^2} \vec{k}_T \cdot \vec{\partial}_{k_T} \right) \frac{A}{\pi\Delta} \int d^2q_\perp \exp \left[-\frac{(\vec{k}_\perp - \vec{q}_\perp)^2}{\Delta} \right] f_{N\perp}^q(x, \vec{q}_\perp)$$

$$f_A^q(x, \vec{k}_\perp) \approx \frac{A}{\pi\Delta} \int d^2q_\perp \exp \left[-\frac{(\vec{k}_\perp - \vec{q}_\perp)^2}{\Delta} \right] f_N^q(x, \vec{q}_\perp)$$

Hadron properties from Lattice QCD

□ Low-lying hadron mass spectrum:

A. Kronfeld, 1209.3468

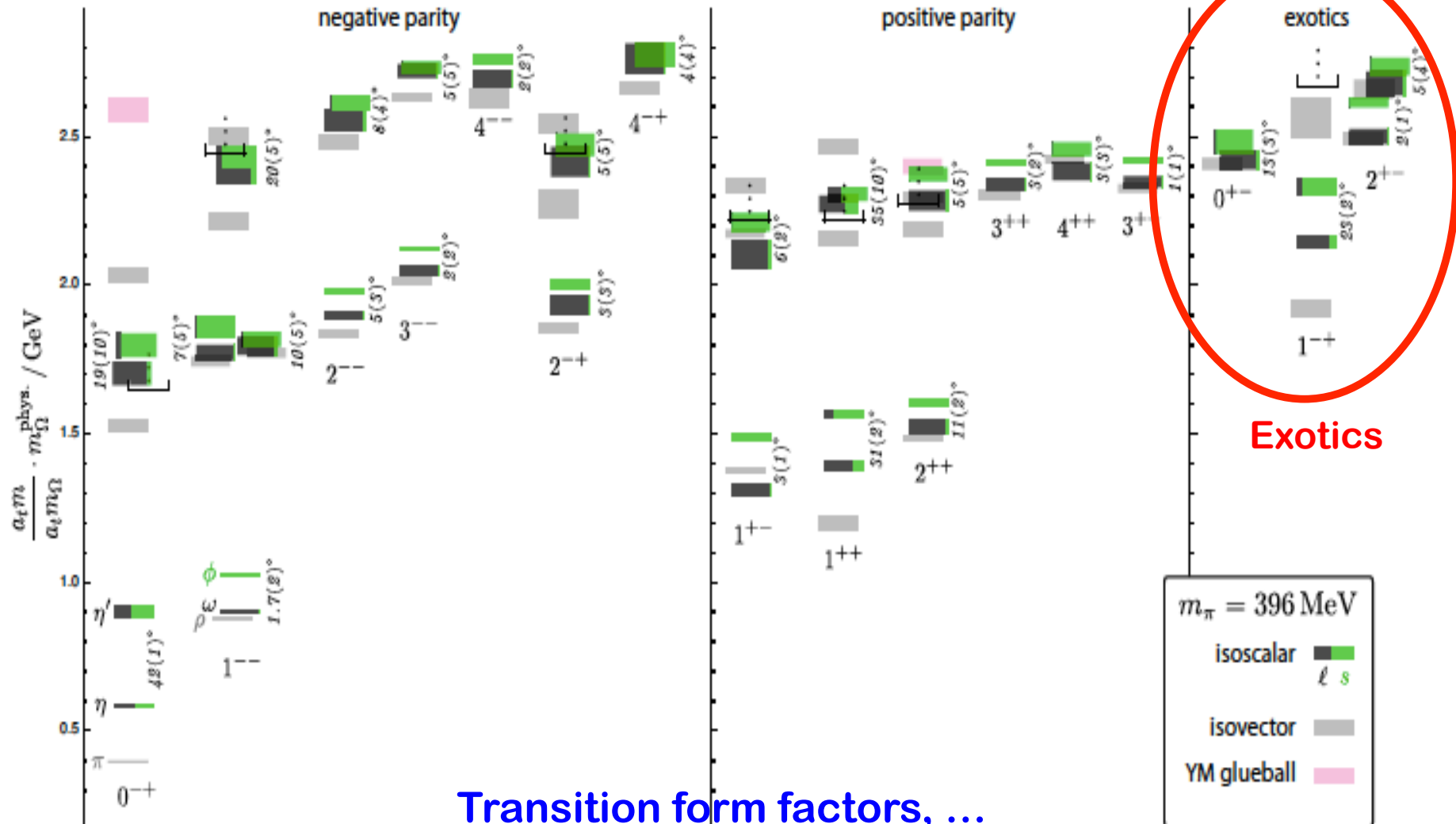


Predictions with limited inputs

Hadron properties from Lattice QCD

□ Meson resonances:

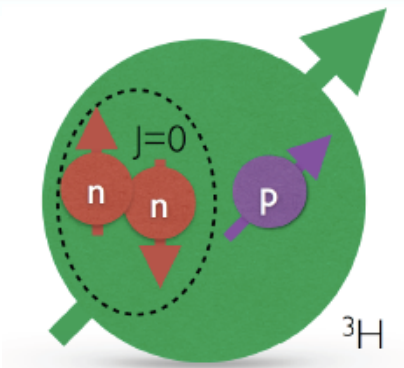
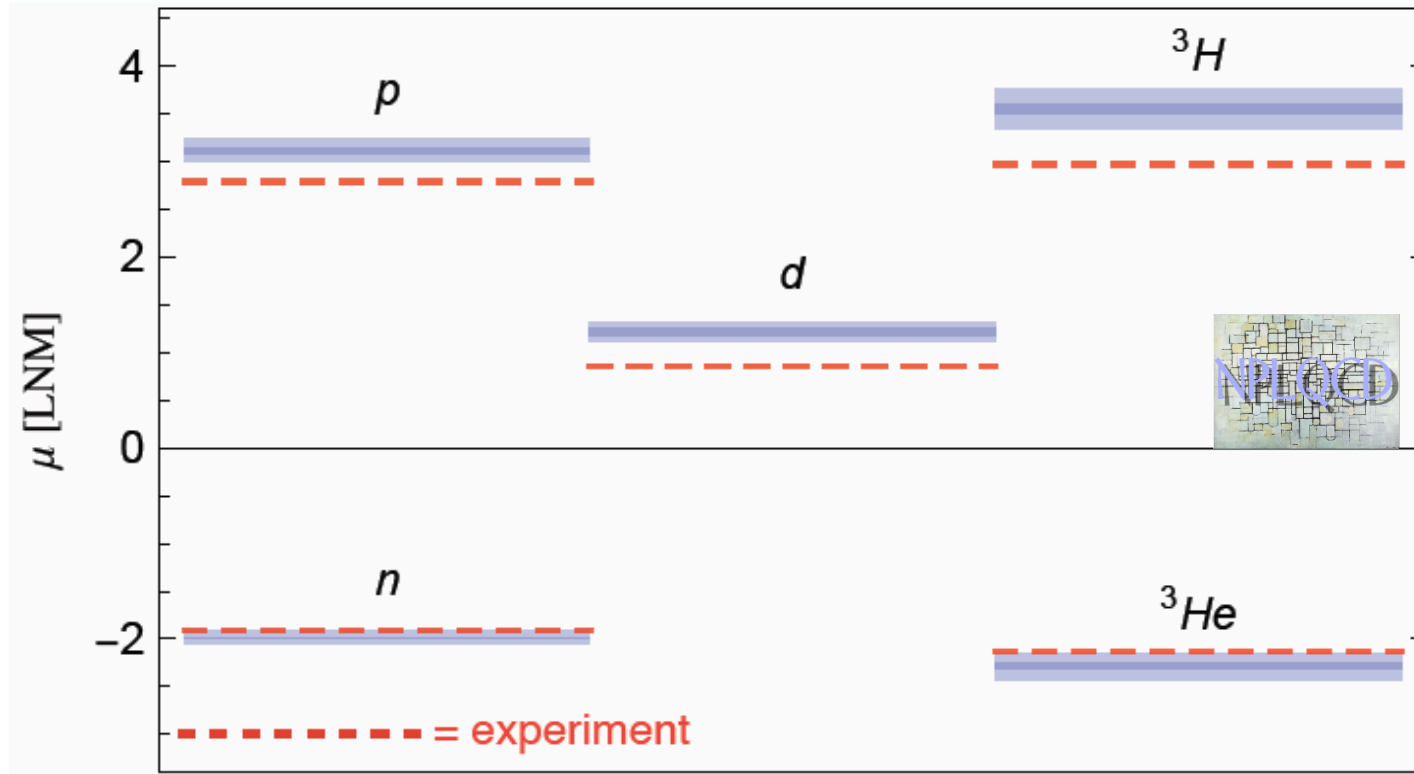
Dudek et al, Phys.Rev. D88 (2013) 094505



Hadron properties from Lattice QCD

□ Magnetic moments:

S.R. Beane et al., Phys.Rev.Lett. 113 (2014) 252001



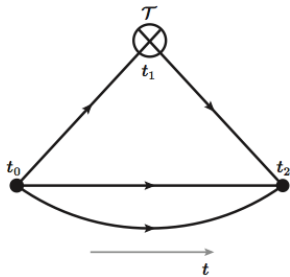
Theory at $m_\pi = 806$ MeV vs. the nature!

*Nuclei are (nearly) collections of nucleons
– shell model phenomenology!*

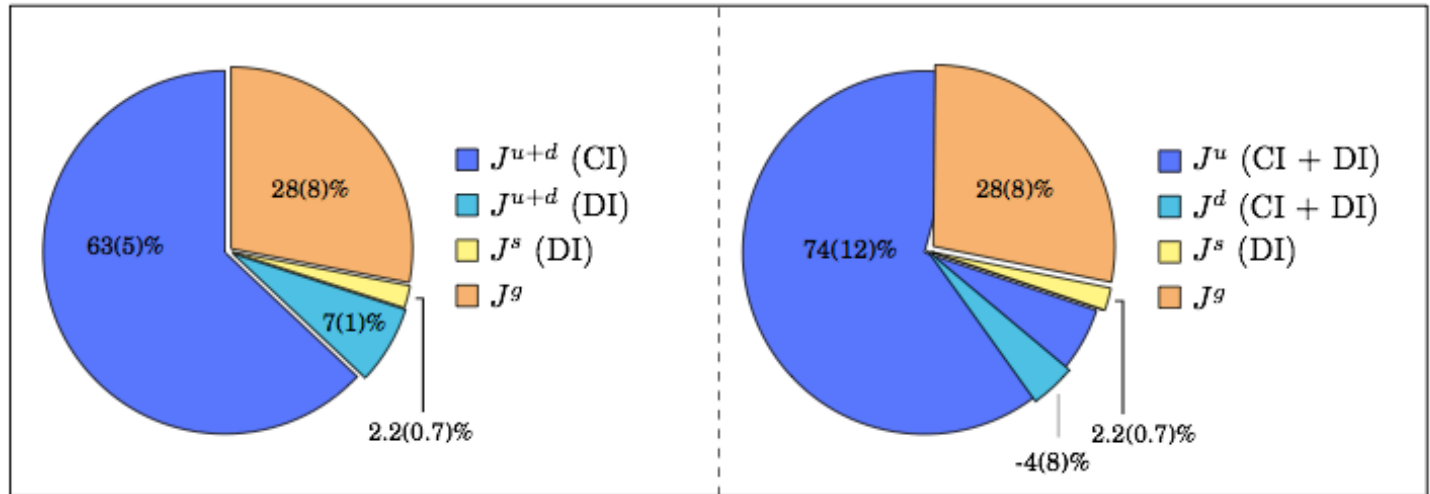
Nucleon spin and OAM from lattice QCD

□ χ QCD Collaboration:

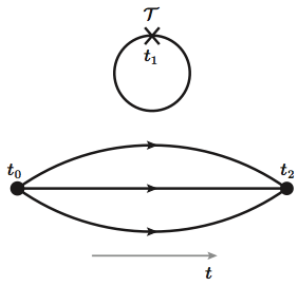
[Deka *et al.* arXiv:1312.4816]



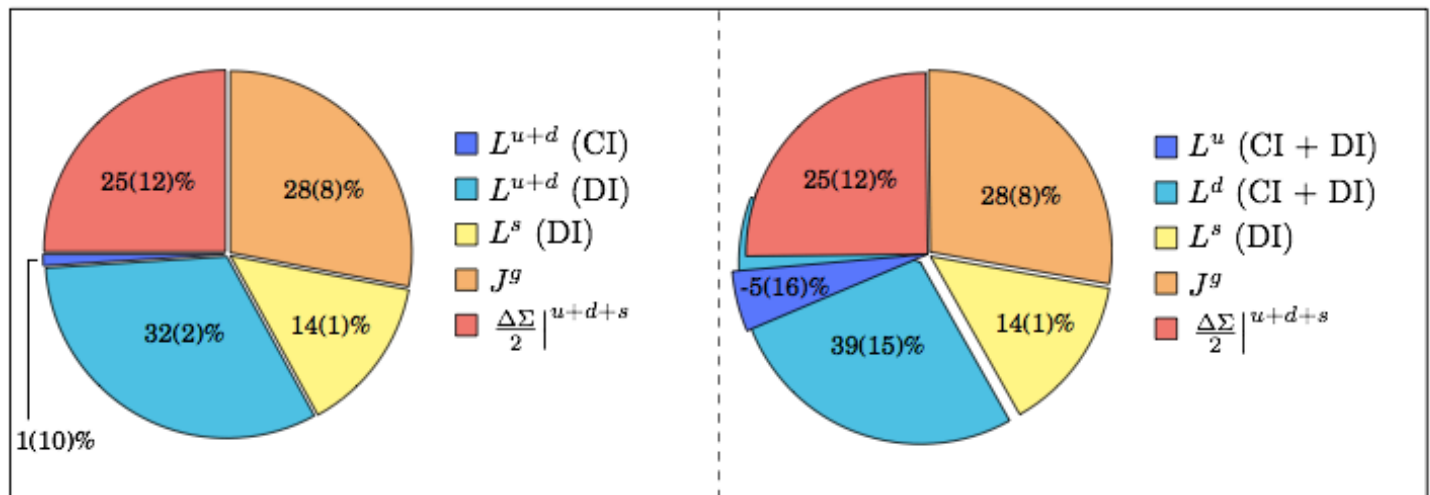
Connected
Interaction (CI)



(b)



Disconnected
Interaction (DI)

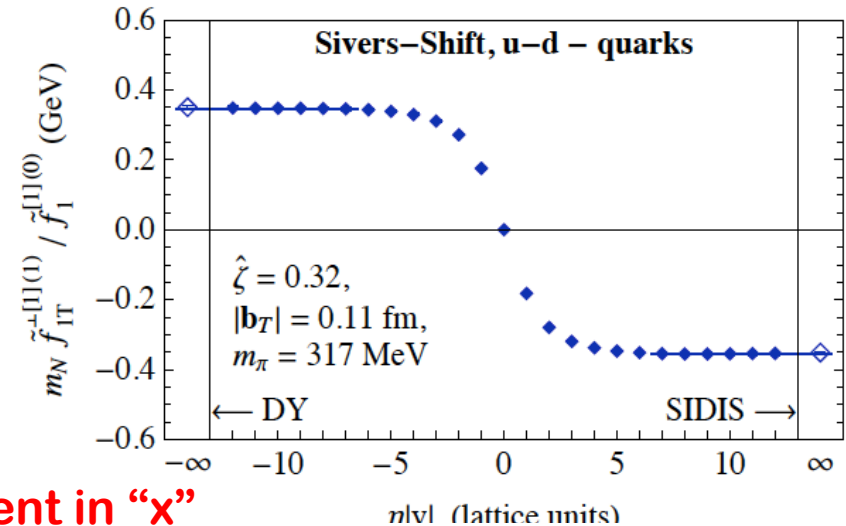
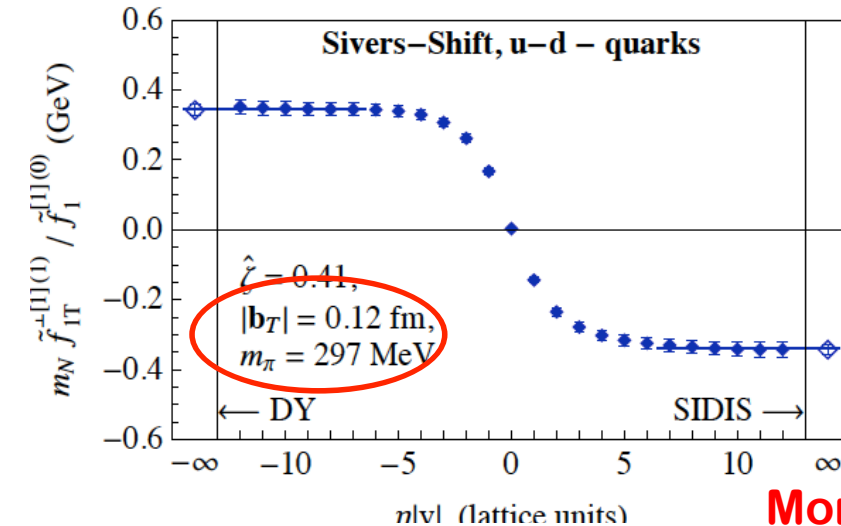


(c)

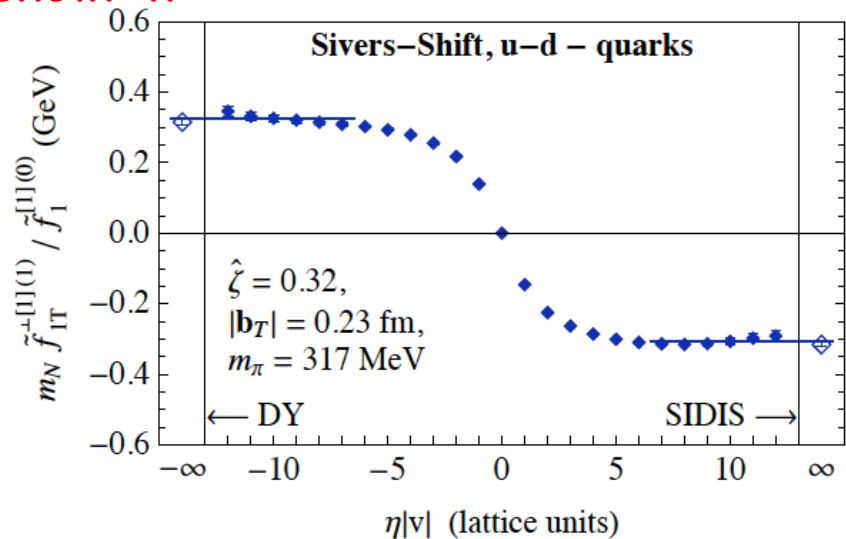
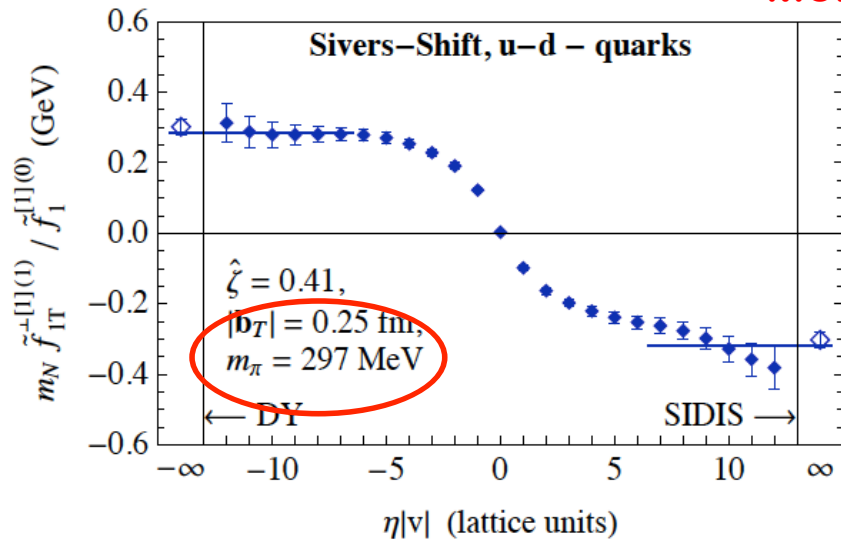
Lattice QCD test of the “sign change”

□ Sample results – Sivers shift:

Musch et al. Phys.Rev. D85 (2012) 094510, ...

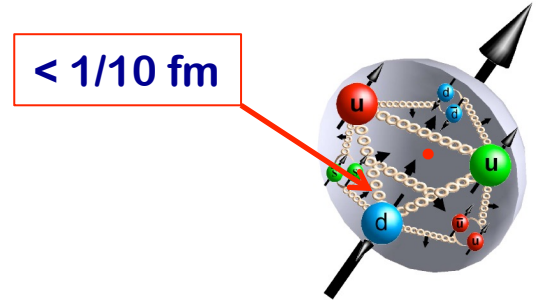


Moment in “x”



Summary

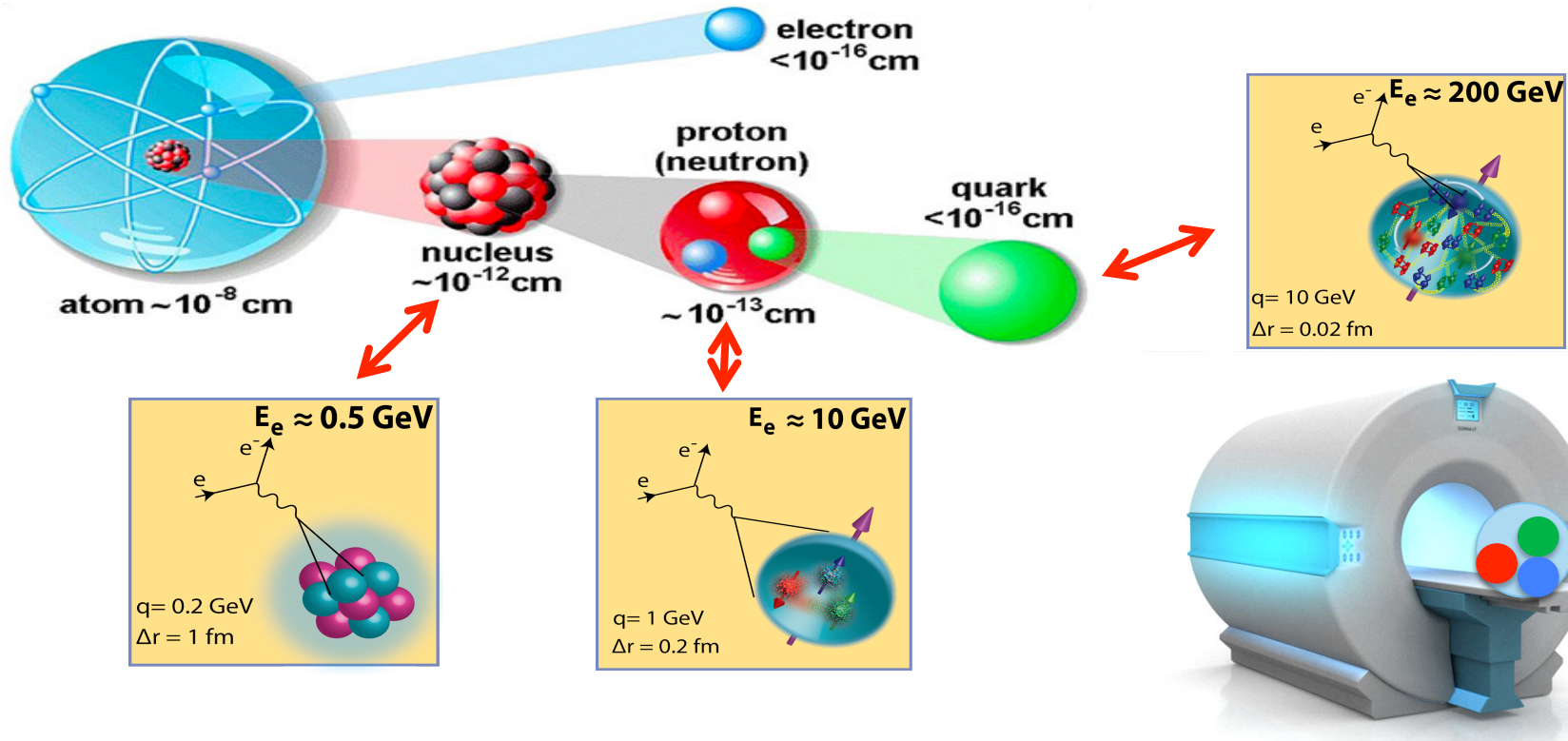
- ❑ QCD has been extremely successful in interpreting and predicting high energy experimental data, but, we still do not know much about hadron structure, and how hadrons are emerged from color charges
- ❑ Lattice QCD has made tremendous progresses, and expected to play a major role in determining hadron properties and structure
- ❑ With JLab12, RHIC, FNAL and facilities around the world, new data will challenge the theory, and new theory ideas will influence the experimental program
- ❑ But, EIC is a ultimate QCD machine, and absolutely needed:
 - 1) **to discover and explore** the quark/gluon structure and properties of hadrons and nuclei,
 - 2) **to search for** hints and clues of color confinement, and
 - 3) **to measure** the color fluctuation and color neutralization



Thanks!

Electron-Ion Collider (EIC)

- A giant “Microscope” – “see” quarks and gluons by breaking the hadron



- Also a sharpest “CT” – “imagine” them without breaking the hadron
– “cat-scan” the nucleon and nuclei with better than 1/10 fm resolution
- Why now?
 - Exp – advances in luminosity, energy reach, detection capability, ...
 - Thy – breakthrough in factorization – “see” confined quarks and gluons, ...

US EIC – Physics vs. Luminosity & Energies

